2003

Solar activity and recent climate change: evaluating the impact of geomagnetic activity on atmospheric circulation

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Evaluating the impact of geomagnetic activity

on atmospheric circulation

A thesis submitted in fulfilment of the requirements for the award of the degree

Doctor of Philosophy

From

The University of Wollongong

By

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School of Geosciences

2003

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"Realization of a potential impact of solar variability on our local environment has progressed a long way in the last few decades, from denial to partial acceptance, but a complete assessment of its reality and magnitude remains a distant goal." (Reid, 1999; page 3)

Abstract

Solar-climate studies have a long and controversial history and the relevance of solar activity to recent climate change remains unclear. Despite prevalent scepticism and uncertainty, recent developments in both solar and atmospheric sciences warrant the reinvestigation of possible solar-climate relationships. The advent of public access to enormous databases of solar and atmospheric variables encourages the reinvestigation of possible solar-climate relationships, particularly those involving solar-modulated geomagnetic activity variations. If further studies demonstrate that climate change has been influenced by geomagnetic activity then research can progress to predicting, modelling, and quantifying the effect. Conversely, if a geomagnetic-activity influence on climate change can be comprehensively disproved researchers can focus on alternative solar or terrestrial climate explanations.

This thesis has evaluated the potential role of solar variability in recent climate change through the statistical examination of the impact of solar-modulated geomagnetic activity on atmospheric circulation. Geomagnetic activity was parameterised using the AA index, while atmospheric circulation was parameterised using the Antarctic, Arctic, and North Atlantic Oscillation indices. These atmospheric circulation indices correspond to the leading causes of variability in the extra-tropical troposphere. Changes in these indices result from large-scale climate changes that are centred on the mid-latitudes. *NCEP/NCAR* reanalysis sea level pressure data were also used to examine the spatial signature of geomagnetic activity effects at the earth's surface. The link between geomagnetic activity and atmospheric circulation was evaluated at daily, annual, and decadal timescales. The analyses were performed on monthly and three-monthly averages of the atmospheric indices to investigate seasonal patterns.

The results indicate that geomagnetic forcing of atmospheric circulation in the northern hemisphere is temporally and seasonally restricted. Moreover, it is controlled by a stratospheric phenomenon known as the quasi-biennial oscillation (QBO), and it is reliant on the interaction of stratospheric and tropospheric circulation. When the data are restricted to January values after 1965, for years in which the January QBO is eastwards, the correlation coefficient between geomagnetic activity and the Arctic Oscillation is strong (r = 0.85; α = 0.05). In the southern hemisphere, statistically significant correlations are evident during March (r = 0.39) and are strongest after the early 1960s,

though the QBO plays no part in the relationship. For both hemispheres the relationships are evident at annual as well as decadal timescales and are therefore of practical significance.

Solar-modulated geomagnetic activity is therefore an important forcing mechanism for recent climate change. Specifically, many of the unexplained aspects of the recent changes in northern hemisphere climate, including the climate regime shift of the early 1960s, can be attributed to the effects of geomagnetic activity in the upper atmosphere. Interannual variations in the North Atlantic Oscillation should no longer be considered as 'climatic noise', while the strong positive trend and decadal variations evident since the 1960s can be attributed, in part, to solar forcing. The results also have implications for the relevance of atmosphere-ocean coupling to the Arctic and North Atlantic Oscillations and the importance of solar activity in southern hemisphere atmospheric circulation. Contrary to claims in the literature, the results of this study indicate that geomagnetic activity is not a viable proxy for solar irradiance variations or the solar-cycle length index. Long-term changes in land temperature are not well correlated to geomagnetic activity and the results of superposed epoch analysis indicate that there is no evidence of geomagnetic forcing of the atmosphere at daily timescales. This indicates that there must be a cumulative effect in the mechanism linking geomagnetic activity to atmospheric circulation that is not discernable in daily data.

Potential mechanisms, coupling geomagnetic activity variations to the lower atmosphere, were evaluated by examining the spatial signature of geomagnetic activity in *NCEP/NCAR* reanalysis zonal wind and temperature data and by comparing geomagnetic activity to solar irradiance, stratospheric aerosol, and total-column ozone data. The reanalysis data extend from the surface to the lower stratosphere in both hemispheres and are available for 17 geopotential heights ranging from 1000 hPa to 10 hPa and 2.5° intervals of latitude and longitude. Through a process of elimination, the results indicate that solar-modulated geomagnetic activity is relevant to tropospheric circulation through the coupling of the upper and middle atmospheres, and the subsequent propagation of stratospheric circulation anomalies to the troposphere through planetary wave activity.

Acknowledgements

My greatest acknowledgement is for my parents, Arnold and Teresa, for giving me the opportunity to undertake tertiary study and to my partner and fellow PhD student, Alexandra Golab, for her infinite support and encouragement.

I also thank my supervisor, Associate Professor Edward Bryant, for his inspiration and support. Ted's interest and enthusiasm, not just during my PhD research but also during my honours year, were a source of motivation and confidence during my studies. Thanks also go to Associate Professor Adam Burnett for his comments and suggestions regarding chapter three. I am also grateful to many of the staff from the School of Geosciences, especially John Reid and John Marthick.

I would also like to thank the numerous individuals and organisations that, by providing online climate and solar data, made this study possible. The appropriate organisations and individuals are acknowledged within the thesis. However, I specifically thank Graham Bartlett, of the UK Meteorological Office, for his efforts in providing me with the Aberdeen pressure data, Peter Thejll, from the Danish Meteorological Institute for solar-cycle length data, and Dirk Wallis for the Lerwick geomagnetic data. Thanks also to the various individuals worldwide that replied to my queries – Mark Baldwin, Patrick O'Sullivan, Rana Moyeed, Kalevi Mursala, Cor Schuurmans, Jay Lawrimore, Alfred Mertins, Joe Chicharo, Rod Nielsen, Davis Pozo Vazquez, and Tamar Atac.

My gratitude also goes to my fellow students and friends who made the whole PhD process enjoyable. In particular, Simon Clarke, Mark Dickson, and Kate Panayotou have been a source of entertainment and support. Finally, I must thank Lily for insisting that I get away from the computer occasionally…

1 Introduction

1.1 Introduction

Can changes in solar activity influence terrestrial climate? This is one of the most enduring questions in the study of climate change. Despite two centuries of research on this topic, it is still unclear to what extent solar variability is relevant to the terrestrial lower atmosphere. Consequently, the idea that solar variability is an important agent of climate change remains controversial.

Part of the uncertainty associated with solar-climate relationships relates to the incorrect assumption, on the part of both researchers and critics, that solar variability can be parameterised solely by the sunspot cycle. Many solar phenomena are, however, better characterised by other solar indices such as geomagnetic activity. While some published studies have considered links between indices of the latter and weather and climate (*Bucha and Bucha, 1998; Cliver et al., 1998*), most only consider daily timescales and relatively few examine annual timescales. Geomagnetic activity, in particular, can potentially represent a wide variety of solar phenomena, and therefore the use of geomagnetic indices in solar climate studies presents an opportunity to examine many of the uncertainties in this field that hinder its acceptance.

There is also the opportunity to apply some of the recent advances in atmospheric science and solar physics to the problem of solar-climate relationships. The *NCEP/NCAR* reanalysis data, available on the internet, provide an excellent opportunity to explore solar influences using observational data at high spatial and temporal resolution. Numerous solar missions have collected important data and increased current understanding of solar processes such as coronal mass ejections and solar irradiance variations. Advances in atmospheric modelling have revealed the importance of the stratosphere to recent climate change – does stratosphere-troposphere coupling also play an important role in solar-climate relationships? The importance of the annular modes to recent climate change has become evident, but with this many questions have arisen about the origin and nature of atmospheric circulation variations associated with these modes.

It is likely, therefore, that the evaluation of the role of geomagnetic activity in recent climate change may provide some elucidation to the sometimes-contentious field of solar-climate relationships and might be relevant to the uncertainties of recent climate change.

1.2 Aim

This thesis has one chief aim – to evaluate the role of geomagnetic activity in recent climate change. To achieve this aim, this thesis tests the hypothesis that solar-modulated geomagnetic activity is an external forcing mechanism of the tropospheric annular modes, which are also known as the Arctic and Antarctic Oscillations. Indices of these oscillations describe recurring patterns (*i.e.*, modes) of atmospheric variability involving changes in polar and midlatitude sea level pressure and zonal wind configurations (*Wallace and Thompson, 2002*). Within this unifying hypothesis, however, there are numerous minor questions relating to solar-climate relationships that this thesis aims to address. The most important relates to mechanisms – no one has yet demonstrated unequivocally how solar variability is coupled to the troposphere, but there are many potential mechanisms that need to be evaluated. Apart from evaluating possible mechanisms, this thesis aims to clarify which aspect of geomagnetic activity is most relevant to atmospheric circulation changes. Other aspects of solar-climate relationships that will be considered include the role of geomagnetic activity in long-term surface temperature changes, and the implications of a link between geomagnetic activity and atmospheric circulation to other solar-climate relationships.

1.3 Outline

Chapter two describes the history of solar-climate relationships. It gives a broad overview of the major developments in the field and describes the important concepts in solar-climate relationships. It also focuses on geomagnetic activity related studies, provides an outline of the development of this specific field, and sums up the current state of knowledge. It also discusses the major shortcomings and contradictions that occur in solar-climate studies.

Chapter three presents the results of analyses examining links between geomagnetic activity and atmospheric circulation through correlations and sliding correlations. It uses the ‘annular’ indices such as the Arctic Oscillation (and the North Atlantic Oscillation) and the Antarctic Oscillation to examine what role geomagnetic activity has, if any, in recent climate changes. Particular attention is paid to the results for the southern hemisphere, which are the first of their kind, as well as the statistical aspect of the analyses.

Chapter four examines links between geomagnetic activity and the lower atmosphere at daily timescales. Once again, it uses atmospheric indices such as the Arctic and Antarctic Oscillations, and it employs the superposed epoch analysis technique. It also reviews some of the recent studies linking daily geomagnetic activity to weather, and evaluates the appropriateness of the superposed epoch technique and the validity of studies that employ it.

Chapter five examines possible mechanisms that may explain the cause-and-effect relationship between solar-modulated changes in geomagnetic activity and tropospheric circulation. It uses the *NCEP/NCAR* reanalysis data to deduce which atmospheric and solar processes are relevant to the results of chapters three and four. In doing so, it evaluates the suitability of possible mechanisms.

Chapter six provides a discussion of the results and then concludes this thesis.

2 Theoretical Framework

2.1 Introduction

The purpose of this chapter is to introduce the major components of the field of solar-climate studies, describe the current state of knowledge in this field, and present some analyses and results that are complementary to the main scope of this thesis. This chapter describes the necessary theoretical background for the study of solar-climate relationships. It covers the history of this field of research, previously suggested links between solar activity and climate, possible mechanisms, and the fundamental concepts of solar activity. This chapter also draws attention to some of the outstanding problems and complications in the field and aspects that are worthy of further investigation. Within this chapter, reviews of some topics are supplemented by analyses designed to explore aspects of solar-climate relationships that have been overlooked in the literature.

The historical development of solar-climate relationships is shown in Table 2.1, which is a summary of some of the more significant discoveries and events within this field. The table merely introduces the many sub-fields of solar-climate relationships, and does not explicitly list all the developments relating to a particular area of solar-climate relationships.

Section 2.2 of this chapter expands on many of the developments shown in Table 2.1, though not necessarily in chronological order. It begins with an overview of the birth of solar-climate relationships, which can be attributed to the prolific astronomer Sir William Herschel, and continues with a description of the solar cycle and the causes and impacts of geomagnetic activity. It also describes the most pressing problems and contentious aspects in the field of solar-climate studies, including:

1. the nature of early studies linking solar and geomagnetic activity to surface pressure and thunderstorms,
2. the controversial link between cosmic rays and clouds,
3. the importance of the Maunder minimum to the credibility of solar-climate relationships,
4. links between solar activity and the stratosphere,
5. the suggestive but debatable relationship between the length of the solar cycle and surface temperatures,
6. the limited literature that considers the predictive value of solar-climate relationships, and
7. the abundant criticisms of solar-climate relationships and solar-climate research.

Section 2.3 focuses specifically on the links between geomagnetic activity and the lower atmosphere. It describes some of the contentious aspects of these links at both daily and decadal timescales. It also introduces the research of *Bucha and Bucha (1998)*, which describes a relationship between the North Atlantic Oscillation and geomagnetic activity. This relationship is expanded upon in chapter three. This chapter concludes with a summary of the main concepts of solar-climate relationships and a discussion of the enduring problems in the field that motivate this study.

2.2 A history of solar-climate relationships

2.2.1 Beginnings

The birth of solar-climate relationships can be attributed to the great astronomer, Sir William Herschel. On April 16, 1801, Herschel read a paper to the Royal Society in London entitled “Observations tending to investigate the Nature of the Sun, in order to find the Causes or Symptoms of its variable Emission of Light and Heat; with Remarks on the Use that may possibly be drawn from Solar Observations.”. Within his presentation, Herschel suggested that with a better understanding of the causes and nature of solar variability, “… some judgement may be formed of the temperature of the seasons we are likely to have.” (*Herschel, 1801*; page 266). Because climate records were not readily available, Herschel tried to link the frequency of sunspots for a number of periods with the price of wheat, under the assumption that the variations in solar radiation are embodied in the abundance (and hence the price) of wheat. The results, however, were vague and uninspiring.

Nevertheless, since then countless papers have been published describing links between various forms of solar activity and climate. Interestingly, papers actually applying any of these links to the prediction of future climate change are extremely rare.

2.2.2 The Solar Cycle

The next important development in the history of solar-climate relationships was the inevitable discovery of the sunspot cycle by Heinrich Schwabe. In 1843 Schwabe published “Sonnen-beobachtungen im jahre 1843” (Solar observations in the year 1843), and using data from 1826-1843 reported a 10-year periodicity in sunspot data. Nowadays, the sunspot cycle is considered to have an 11-year periodicity, though the length of each cycle can vary from 9 to 14 years (*Baliunas and Soon, 1995*). This quasi-regular periodicity in the solar cycle is fortuitous for some solar-climate researchers, because many studies rely on the spectral peaks in climate data at ~11 years as their sole evidence of a solar influence on the terrestrial atmosphere (see, for example, *Currie, 1974; Currie, 1996; Currie and Vines, 1996* and other of Currie’s work). Conversely, if the solar-cycle were aperiodic, the statistical significance of solar-climate relationships that rely on correlations would not be so limited by the effect of serial correlation on effective sample size (see chapter three).

The most pertinent aspect of the solar cycle, for this and other solar-climate studies, is the change in the solar environment between solar maximum and solar minimum, which involves more than just the frequency of sunspots. The relevant changes include the frequency of sunspots *and* faculae, the frequency and intensity of solar flares, and changes in various solar phenomena that influence the earth's magnetic field.

Sunspots and faculae. Sunspots are relatively cool, dark areas on the sun's photosphere (*Lang, 2001*). It is obvious that the number of sunspots visible on the sun's surface varies from solar minimum to solar maximum (Figure 2.1); what is not so obvious is that sunspots are generally accompanied by brighter, hotter areas called faculae, which more than compensate for the reduced irradiance from the dark sunspot areas. In fact, at solar maximum the overall increase in solar irradiance from faculae exceeds the decrease from sunspots by a factor of 1.5 (*Lean et al., 1995*). The relative impact of sunspots and faculae to solar irradiance varies over the solar spectrum – the influence of faculae is dominant at ultraviolet wavelengths and decreases at longer wavelengths so that at a wavelength of 1.6 μm the impact of faculae is limited (*Lean, 2000*). Satellite-borne pyrheliometers have confirmed that total solar irradiance does indeed vary over the course of the solar cycle, by about 0.1% (*Foukal, 1998*). A good discussion of the solar irradiance changes can be found in *Hoyt and Schatten (1993)*, *Fröhlich and Lean (1998)*, and *Solanki and Fligge (1999)*.

Solar flares. Solar flares are associated with, but not necessarily caused by, sunspots (*Lang, 2001*). As such, the amount of solar flare activity varies with the sunspot cycle (*Lin, 1998*). This is clearly evident when the solar flare index is compared to the sunspot number. Figure 2.2 shows that increased flare activity coincides with solar maxima. The flare index[1] is a measure of the time and intensity of solar flares (see *Ataç and Özgüç, 1996*).

Flares are potentially relevant to solar-climate relationships for two reasons. Firstly, solar flares contribute to irradiance variations, especially in the climatically important wavelengths involving extreme ultraviolet radiation (*Antonova and Nusinov, 1996*). During a solar flare, extreme ultraviolet radiation can be increased by a factor of 10 or more (*Foukal, 1998*). Secondly, some solar flares are accompanied by an enormous flux of energetic particles (mainly electrons but also protons) with energies up to 10 MeV (*Zirin, 1988*). Apart from the dangers these energetic particles pose for high-altitude satellites (*Joselyn, 1998*), they also cause ionisation of the earth's atmosphere above the high-latitude stratopause (*Dickinson, 1975*). Not all solar flares involve the flux of energetic particles into the earth's atmosphere; the few that do are interchangeably referred to as solar proton events (*Antonova and Nusinov, 1996*), solar cosmic ray events (*Dickinson, 1975*), or solar energetic particle events (*Lin, 1998*). Many studies focussing on daily solar-climate links (sun-weather relationships) report an apparent response of the atmosphere to solar flare activity (see, for instance, *Pudovkin and Babushkina, 1992a; Gabis and Troshichev, 2000*).

Coronal mass ejections, the slow solar wind, and coronal holes. These three solar phenomena can be considered the drivers of geomagnetic activity; variations in the frequency, composition, and intensity of these events result in variations in the magnetosphere and hence geomagnetic activity. They are described here only briefly, as the physics of these events are of limited relevance to solar-climate relationships. The aspects of geomagnetic activity that are potentially relevant to solar-climate relationships are discussed later within this chapter.

The magnetosphere is the region of space that is influenced by the earth's magnetic field (*Lyons, 2000*). Undisturbed by the sun and the solar wind, the earth's magnetosphere

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[1] It is available online from the Bogazici University Kandilli Observatory (Istanbul, Turkey) and commences in 1976. (http://www.koeri.boun.edu.tr/astronomy/findex.html)

would resemble a simple dipolar magnetic field, as shown in Figure 2.3 (*Hopgood and Barton, 1987*). However, because the sun's magnetic field is embedded within its various forms of ejecta, the magnetosphere is constrained by solar activity and instead of approximating a sphere the magnetosphere contains a 'tail' on the nightward side. Under normal circumstances, it resembles the pattern shown in Figure 2.4a (from *Lyons, 2000*). The solar magnetic field and the magnetosphere are aligned in the same direction (northward) and remain closed to one another. However, when the solar magnetic field (embedded in either the solar wind or coronal mass ejections) has a southward component the magnetic field lines are joined and the magnetosphere is 'open' (Figure 2.4b). This allows the transfer of energy from the solar wind to the magnetosphere[2], and results in variations in the strength and behaviour of the magnetic field. The three main solar events that lead to the coupling of the sun and the magnetosphere are coronal mass ejections, variations in the slow solar wind, and coronal holes. These are described, in turn, below.

Coronal mass ejections are large 'clouds' of plasma emitted from the outer layer of the sun's atmosphere (the corona) and chromosphere (*Webb, 2000*). As well as the energetic particles that make up coronal mass ejections, these large solar clouds are also embedded with the sun's magnetic field. The particles and the magnetic field contained within a coronal mass ejection interact with the earth's magnetic field to cause geomagnetic storms. *Rees (1995)* describes the sequence of events involving coronal mass ejections that lead to magnetospheric disturbances and ultimately changes in the thermosphere. Coronal mass ejections typically travel at speeds between 20 kms^{-1} and 2,000 kms^{-1} (*Cane, 2000*), and therefore require ~2-4 days to reach the earth. This

[2] A southward component to the solar magnetic field is not always necessary for geomagnetic disturbances to occur. According to *Rees (1995)*, satellite observations indicate that under certain pressure conditions in the solar wind, geomagnetic activity can result even with a northward magnetic field. Alternatively, *Gosling et al. (1991)* report that the speed of a coronal mass ejection as it leaves the sun is the most important factor relating to its effectiveness in causing geomagnetic disturbances. *Schreiber (1998)* found that the southward component of the solar magnetic field is most important (for geomagnetic activity) during the descending phase of the solar cycle, while the velocity of the solar wind has a greater influence during the ascending phase.

makes it possible to predict the arrival of a geomagnetic storm[3] and, perhaps, any associated meteorological impacts. The possible climatic significance of these geomagnetic disturbances is outlined in section 2.3.

Figure 2.5 is a chronograph picture[4] of an unusually narrow coronal mass ejection that occurred on June 2nd, 1998. The white circle at the centre of the image marks the position of the sun – the black disk obscures the sun to allow the chronograph to observe the corona. The figure shows the coronal mass ejection streaming off to the lower right corner of the image. From this, it is obvious that not all coronal mass ejections are directed toward the earth. In fact, during solar maxima only about 70 coronal mass ejections per year are earth-directed (*Lang, 2001*). The frequency of coronal mass ejections closely follows the solar cycle (*Hudson, 1997*). *Webb and Howard (1994)* used data spanning 1972 to 1989 to show that the rate of occurrence of coronal mass ejections is up to three per day during solar maximum and lower than 0.5 per day during solar minimum.

Although there is an element of uncertainty regarding the solar origin of non-recurrent geomagnetic activity, *Landi et al. (1998)* conclude that a 'large fraction' of geomagnetic storms is related to coronal mass ejections. Similarly, *Gosling et al. (1991)* report that between August 1978 and October 1982, 36 out of the 37 major geomagnetic storms in that period were related to coronal mass ejections. However, the relative importance of coronal mass ejections to geomagnetic activity varies over the solar cycle. During solar maxima, their contribution to geomagnetic activity is ~50%, compared to <10% during solar minima (*Richmond and Lu, 2000*).

The second solar phenomenon that drives geomagnetic activity is the solar wind. The solar wind is, in the simplest view, charged particles (typically protons) from the sun emitted into interplanetary space at velocities between 300 and 700 kms^{-1} (*Goldstein,*

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[3] See *Webb et al. (2002)* for a description of an upcoming project for the detection and measurement of coronal mass ejections and the prediction of their arrival at earth.

[4] Courtesy of SOHO/LASCO consortium. SOHO is a project of international cooperation between ESA and NASA. See http://sohowww.nascom.nasa.gov/ for more information.

1998). More specifically, the solar wind is derived from the corona and is plasma embedded with the solar magnetic field and consisting of high-energy protons and electrons (*Akasofu, 1998*). Because the solar wind is plasma, it 'drags' with it some of the solar magnetic flux, which once it has left the sun, is known as the interplanetary magnetic field (*Lockwood et al., 1999*). It is interesting to note that although the energy contained in the solar wind is only one-millionth that of the total solar irradiance (*Lyons, 2000*), it can still cause large disturbances to the earth's magnetosphere and upper atmosphere. There are two types of solar wind – a fast solar wind that is relatively unchanged over the course of the solar cycle, and the slow solar wind (*Lang, 2001*). Changes in the properties of the slow solar wind, such as magnetic field direction and strength, density, and speed, result in changes to geomagnetic activity. The relative importance of variations in the slow solar wind to geomagnetic activity is ~20% regardless of the solar cycle state (*Richardson et al., 2000*).

The third driver of geomagnetic storms is coronal holes, which are associated with high-speed solar streams. Coronal holes correspond to magnetic 'loops' on the solar corona. However, instead of being closed (that is, with both ends embedded in the sun), one end of the loop extends out into interplanetary space, emitting a high-speed solar wind (*Lang, 2001*). Figure 2.6 shows an exceptionally large coronal hole (outlined) with arrows drawing attention to the outgoing high-speed solar wind. Coronal holes are generally associated with recurrent geomagnetic activity (*Chen, 1997*) such as the 27-day cycle described by *Chree (1913)*. The recurrent activity is the result of the 27-day solar rotation – geomagnetic activity peaks when a coronal hole is earth-directed. Their relative contribution to geomagnetic activity is ~30% during solar maxima and 70% during solar minima (*Richardson et al., 2000*). They are most effective during the descending phase of the solar cycle (*Tsurutani and Gonzalez, 1998*). The impact that coronal holes have on the magnetosphere is markedly different to that of coronal mass ejections. Coronal mass ejections generally lead to larger, shorter-lived disturbances, while the high-speed solar wind from coronal holes causes less intense disturbances of longer duration (*Watari and Watanabe, 1998*).

This section has described the numerous changes in the solar environment over the course of the solar cycle. Three main changes were described – solar irradiance changes through sunspots and faculae, changes in solar flare frequency and intensity, and changes in the various coronal phenomena that drive geomagnetic storms. The links between these changes and the terrestrial atmosphere are summarised in Figure 2.7 (*Baker, 2000)*. From a solar-climate perspective, an important solar-terrestrial relationship that has not been included in *Baker's (2000)* figure is the effect of cosmic rays and energetic particles on atmospheric ionisation (described in *Ney, 1959*), which is evident in all layers of the atmosphere. In the figure, variations in sunspots and faculae are embodied in the link between the photosphere and ultraviolet and visible light, and finally the atmosphere. Changes in solar flare frequency and intensity are included in the link between the three outer solar layers to transient events. Changes in the solar wind follow a different path to the terrestrial atmosphere and involve geomagnetic activity effects on the upper atmosphere, which are described in the following section.

2.2.3 Geomagnetic Activity

In 1852, Sabine declared that the period and epochs of the sunspot record and geomagnetic activity are "absolutely identical" (*Sabine, 1852*; page 121). Sabine's revelation that geomagnetic and solar variations are related marks the beginning of the field of solar-terrestrial physics (*Cliver, 1994*). Figure 2.8 shows the similarity between solar activity, represented by the sunspot number, and geomagnetic activity, represented by the AA index (for the period 1868-2000, r = 0.60). There are, however, some differences between the two that are of great importance to solar-climate relationships, which are described later within this chapter. The causes of geomagnetic activity have been described in the previous section. This section reviews the impact that geomagnetic activity, in particular geomagnetic storms, has on the terrestrial atmosphere.

Three aspects of geomagnetic activity are (potentially) climatologically relevant. Firstly, geomagnetic activity exerts a profound influence on the earth's thermosphere and to some degree the mesosphere (see, for example, the review in *Laštovička, 1996*). The possibility that the upper and middle/lower atmospheres are to some degree coupled is one way that geomagnetic activity variations might influence climate. Secondly, geomagnetic activity influences the flux of cosmic rays entering the atmosphere

(*Forbush, 1954*), which in turn influences atmospheric ionisation and electric currents. This has been suggested by some as a mechanism by which solar activity influences cloud cover and, ultimately, climate (see section 2.2.8). Finally, because the solar cycle and geomagnetic activity are closely related, it has been suggested that geomagnetic activity variations can possibly be used as an index of solar irradiance (*Cliver et al. 1998, Lockwood, 2001*). These aspects are discussed, in turn, below.

Upper atmospheric response to geomagnetic storms. Figure 2.9 shows the structure of the earth's atmosphere. A geomagnetic storm is a period of intense energy input into the upper atmosphere from the magnetosphere (*Fuller-Rowell et al., 1994, 1997*). For example, *Lu et al. (1998)* report that ~400 GW of energy was deposited into the mesosphere during a two-day geomagnetic disturbance in January 1997. The injection of energetic particles from the magnetosphere initiates many changes in the thermosphere and ionosphere. Geomagnetic storms influence the structure, composition, dynamics, temperature, and electric fields of the upper atmosphere (*Forbes et al., 1996; Prölss and Roemer, 2000; Richmond and Lu, 2000*). These changes are brought about by three processes – joule heating, auroral particle precipitation, and ion drag (*Fuller-Rowell et al., 1997; Richmond and Lu, 2000*). Despite the large change in the upper atmosphere during geomagnetic storms, the potential impact on the lower atmosphere (and climate) is limited. This is mainly because most of the energy is deposited in the lower thermosphere, at a height of 115 km, and largely affects the atmosphere above this level (*Fuller-Rowell et al, 1997*).

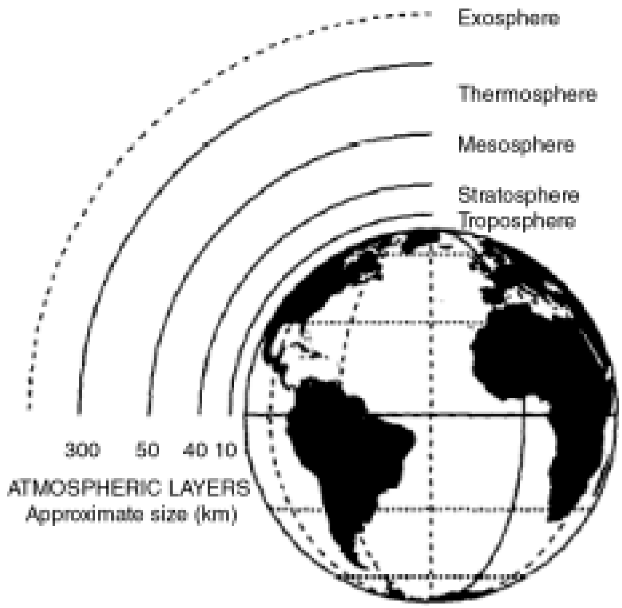

Figure 2.9. Structure of the earth's atmosphere (modified from *Storini, 2001*). Changes in geomagnetic activity have a profound impact on the thermosphere, and to a lesser degree, the mesosphere. It is not clear, however, how geomagnetic activity can impact the stratosphere and troposphere.

An understanding of the upper atmospheric response to geomagnetic activity is limited by a lack of observational data. Nevertheless, there are a number of responses that may be relevant to the lower atmosphere. For instance, *Bogdanov and Leont'yev (1991)* have shown that vertical winds of considerable velocity occur in the thermosphere, and that the direction of the vertical winds (descending/ascending) is affected by aurora (which are the product of heightened geomagnetic activity). To explain observed correlations between the North Atlantic Oscillation and geomagnetic activity, *Bucha and Bucha (1998)* suggested that the downward winds generated in the thermosphere during geomagnetic storms can influence the strength of the northern hemisphere jet stream. Although there is no direct evidence that vertical winds in the thermosphere can influence the lower atmosphere, this mechanism is worth considering (see chapter five).

Changes to the composition of the upper atmosphere during a geomagnetic storm might also influence the lower atmosphere. There are numerous compositional changes to the thermosphere resulting from geomagnetic activity (see, for example, *Engebretson and Maursberger, 1983*). One of particular interest, because of its potential relevance to climate, is the change in nitrogen oxide. *Fuller-Rowell et al. (1997)* report that the nitrogen oxide generated in the lower thermosphere during solar and geomagnetic activity can be transported downward by vertical winds, and once in the middle atmosphere (at an altitude of 40-50 km), it can destroy ozone[5]. These processes and the importance of energetic electron precipitation (associated with the solar wind) in the middle atmosphere and stratospheric ozone were examined in *Callis et al. (2001)*[6]. Their results suggest the possibility of a dynamic coupling of the lower and middle/upper atmosphere via atmospheric chemistry.

Fuller-Rowell et al. (1997) also suggest that the changes in thermospheric circulation during geomagnetic storms may influence the transmission of planetary waves from the lower atmosphere. Such a mechanism, whereby solar-induced changes to the atmosphere influence the troposphere through planetary wave coupling, is described in *Arnold and Robinson (1998, 2001)*, and evaluated in chapter five.

One further consideration of the potential climatic impact of geomagnetic activity relates to the electric currents generated during such disturbances. The thermospheric winds generated during a geomagnetic storm move the electrically conductive ionospheric plasma through the earth's magnetic field, creating electric currents in the ionosphere which can alter the vertical electric field at the earth's surface (*Fuller-Rowell et al., 1997*). The geomagnetic disturbances can also induce currents on the earth's surface, sometimes to the detriment of pipelines and power stations (*Joselyn, 1998*). For instance, during March 1989 a geomagnetic activity induced current damaged the Hydro-Québec power network (*Pirjola et al., 2000; Siscoe, 2000*). The possible climatic implications of these electric currents are described in section 2.2.8, and relate mainly to the 'electrofreezing' mechanism suggested in *Tinsley (1996b)*.

Cosmic rays and the Forbush decrease. Under normal solar wind conditions there are more than 10^{18} galactic cosmic rays per second arriving at the top of the earth's atmosphere (*Jokipii, 1998*). These cosmic rays are mainly protons with energies of ~1

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[5] *Fuller-Rowell et al. (1997)* report that this process has been observed and modelled for solar proton events, but not for nitrogen oxide produced during geomagnetic storms. Furthermore, this process is generally limited to the polar night period, especially during the solstice, as nitrogen oxide undergoes photodissociation.

[6] *Callis et al. (2001)* used a number of 19-year simulations as well as observational data to examine the effects of energetic electron precipitation and ultraviolet radiation variations on the global ozone columns.

GeV, and are the main source of atmospheric ionisation between altitudes of 1-50 km (*Dickinson, 1975*), though most galactic cosmic ray ionisation occurs at altitudes between 10-20 km (*Tinsley et al., 1989*).

Forbush (1954) used cosmic-ray ionisation data from four locations – Godhavn (Denmark), Cheltenham (U.S.), Huancayo (Peru), and Christchurch (New Zealand) – to show that a variation in ionisation of about 4% between 1937 and 1952 was negatively correlated to the sunspot number. Further investigation led him to conclude that there is a relationship between cosmic-ray decreases and geomagnetic activity, and that "major transient decreases in cosmic-ray intensity occur during magnetic disturbances." (*Forbush, 1954*; page 525). The relationship described in *Forbush (1954, 1958)* is now termed the Forbush decrease[7] and involves the modulation of cosmic-ray flux by the solar wind. Cosmic rays are entrained by the magnetic field of the outward moving solar wind (*Jokipii, 1998*); the interplanetary (solar) magnetic field therefore acts as a barrier to cosmic rays, and the amount of cosmic ray 'blocking' depends on the strength of the magnetic field (*Lang, 2001*). The largest Forbush decreases result in ionisation decreases of up to 30% at polar latitudes (*Bazilevskaya et al., 2000*) and are associated with fast coronal mass ejections[8] (*Cane, 2000*). Figure 2.10 shows the close relationship between solar activity (as represented by the sunspot number) and cosmic-ray flux. It is important to note, however, that geomagnetic activity is not a perfect proxy for Forbush decrease magnitude, largely because geomagnetic activity is affected by conditions near the earth while the Forbush decrease of cosmic rays occurs over a larger area in the heliosphere (*Belov et al., 2001*).

Geomagnetic activity as a proxy for solar irradiance. *Cliver et al. (1998)* compared decadal averages of geomagnetic activity and terrestrial surface temperature records, and found that the two are strongly correlated (r = 0.90). Based on their results, *Cliver et al. (1998)* hypothesised that variations in the geomagnetic activity index relate to

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[7] The term Forbush decrease is generally only applied to short-term, non-recurrent decreases associated with transient events, such as coronal mass ejections (*Cane, 2000*).

[8] *Cane (2000)* also notes, however, that coronal mass ejections are of limited importance to the long-term modulation of cosmic rays seen over the course of the solar cycle.

long-term variations in solar irradiance. This suggestion is supported by the results of *Lockwood et al. (1999)* who found that the coronal source flux (which is well represented by indices of geomagnetic activity) is strongly correlated to solar irradiance measurements (r = 0.84). *Lockwood (2001)* also reports that the indices of solar cycle length, which are often used as a proxy for solar irradiance (see section 2.2.11), show some similarities to geomagnetic activity indices.

As well as the possible similarities between geomagnetic activity and long-term solar irradiance changes, a similar relationship may also exist at the daily timescale. The largest coronal mass ejections are associated with, but not caused by, solar flares. Section 2.2.2 has already indicated that increases in solar ultraviolet radiation are associated with large flares; this is another way in which geomagnetic activity may be a useful proxy for solar irradiance.

2.2.4 Geomagnetic Activity and the Sunspot Cycle

The previous sections have described the similarities between the sunspot number, which is the most commonly used index of solar activity, and geomagnetic activity. There are fundamental differences, however, some of which have been noted by solar-climate researchers, and all of which are obvious when the two indices are compared. These are shown in Figure 2.11, which uses an index of geomagnetic activity known as the 'AA' index (Amplitude Antipodal) that is described in section 2.2.5. It is important for solar-climate researchers to note these differences because they will have some bearing on the outcome of statistical analyses.

Firstly, geomagnetic activity contains an upward trend that is not mirrored in the sunspot number (Figure 2.11). The trend has particular significance for solar-climate relationships, as a similar long-term trend is evident in global temperatures. *Lockwood et al. (1999)* relate this increase in geomagnetic activity to a doubling of the solar coronal magnetic field over the last 100 years, which they also suggest is related to the sun's luminosity.

A second important difference is that maxima of geomagnetic activity tend to occur a number of years after the corresponding sunspot maxima, as the following analyses demonstrate. In Figure 2.12a, years of geomagnetic and sunspot maxima were designated as those that exceeded all adjacent values for ±3 years. By comparing the timing of geomagnetic activity maxima with the timing of the nearest sunspot maxima, it is evident that the lag between peaks in the two indices range from -2 to +5 years[9]. These calculations reveal that the average lag is 1.42 years. By examining the time series of the two indices, it is also evident that instances where the geomagnetic maxima lead the sunspot maxima (1882, 1926, 1978), as represented by negative lags, correspond to ‘double maxima’. In each instance, another geomagnetic maximum occurs four years later – this result coincides with the suggestion, by *Clúa de Gonzalez et al. (1993)*, that a 4.4-year periodicity in geomagnetic activity is the result of the ‘dual-peak’ structure in geomagnetic maxima. A similar analysis of the correspondence between geomagnetic and sunspot minima (Figure 2.12b) shows that in nearly all instances, a geomagnetic minimum occurs in the same year, or the year after, a sunspot minimum. The two exceptions are the geomagnetic minimum in 1949, which appears to coincide with a sunspot maximum, and the geomagnetic minimum in 1980, which lags the sunspot minimum by four years.

Another important difference, especially for the statistical aspect of solar-climate relationships, is that geomagnetic activity exhibits substantial short-term (2-5 year) variations, whereas variability in the sunspot number is largely limited to the decadal timescale. This is evident in Figure 2.13, which shows power spectra for the two time series. These variations need to be filtered out if geomagnetic activity is to be used for comparisons with decadal-scale climate variations (see chapter three). Conversely, the short-term variations can be isolated to examine solar-climate relationships at timescales that are unavailable when the sunspot number is used to parameterise solar activity.

[9] The geomagnetic activity maximum in 1943 was excluded from the analyses because it coincides with a sunspot minimum.

There are also a number of aspects relating to the temporal behaviour of geomagnetic activity that are pertinent to solar-climate relationships. The first is the seasonal variation of geomagnetic activity – geomagnetic activity displays maxima at the equinoxes, which are especially prominent for intense geomagnetic storms (*Gonzalez et al., 1994; Bell et al., 1997*). Figure 2.14 shows the monthly average of the geomagnetic AA index from 1868 to 1999 – note the peaks in March and September. The equinoctial peaks are even more pronounced when the number of geomagnetic storm days, between 1868 and 1998, are plotted (Figure 2.15). *Schreiber (1998)* notes, however, that the equinoctial maxima in geomagnetic activity are mainly evident in the declining phase of the solar cycle, whereas during the ascending phase the semi-annual maxima occur at the beginning of April and March. The reason for these maxima is not fully understood yet but *Clúa de Gonzalez et al. (1993, 2001)* and *Schreiber (1998)* describe the most likely mechanisms, which generally relate to the geometry between the earth and the sun. There is also an enigmatic tendency for very large geomagnetic storms to occur in July (see *Clúa de Gonzalez et al., 2001*), which has not been explained.

Geomagnetic activity is also different to sunspot activity because it is variable on daily timescales, largely through the impacts of coronal mass ejections. Sunspots, conversely, do not have strong daily variance and cannot accommodate the analysis of solar-weather relationships. The use of geomagnetic activity as a solar proxy has led to a solar-climate field of study that focuses on sun-weather relationships. In fact, most studies linking geomagnetic activity to the lower atmosphere focus on daily timescales.

Finally, as the previous sections have shown, geomagnetic activity represents a whole suite of solar-terrestrial relationships, and the geomagnetic AA index can possibly act as a proxy for many solar phenomena, such as flare activity and solar irradiance changes. In that regard, it is important to explain, as *Labitzke (2001)* did with the use of the 10.7 cm solar flux as an index of solar activity, that the use of geomagnetic activity indices throughout this study does not imply a direct causal relationship between the state of the earth's magnetic field and the climate of the lower atmosphere. Geomagnetic activity is simply used as a proxy for the various solar-terrestrial changes described in previous sections. The aspect of geomagnetic activity that is most relevant to climate change is examined in chapter five.

2.2.5 Indices of Geomagnetic Activity

In 1972, Mayaud developed the AA index and showed that it is superior to many other existing geomagnetic indices. Its benefits are especially pertinent to solar-climate relationships. A general overview of some of the different geomagnetic indices is available online from the *National Geophysical Data Center*[10] and in *Hopgood and Barton (1987)*, and is as follows:

Geomagnetic observatories worldwide measure the state of the earth's magnetic field over three hour intervals in a logarithmic scale ranging from 0-9, known as the *K*-index. The daily average from 12 globally distributed stations is known as the planetary index, *Kp*. When converted to a linear scale, the *Kp* index becomes the *Ap* index (the 'A' meaning 'amplitude'). The *Kp* and *Ap* indices have been used extensively in studies linking geomagnetic activity to the lower atmosphere. However, solar climate studies sometimes use a different index – the AA index. The AA index is similar to the planetary index (*Ap*) but is instead based on data from two antipodal stations, Hartland (England) and Canberra (Australia). Like the Ap index, it is measured in nanoTesla (nT).

Factors that limit the global usefulness of geomagnetic indices include the influence of the daily maximum at each station, occurring at night (in local time), and the seasonal maximum at the summer solstice (*Clilverd et al, 1998*). The use of antipodal stations for the calculation of the AA index overcomes both these problems *(Mayaud, 1972)*. The AA index and other geomagnetic indices are available from the *NOAA NGDC Solar Terrestrial Physics Division* Internet site[11]. It boasts a relatively long record – unlike the *Ap* index, which only spans 1932-1998, the AA index is currently available from 1868-1998. Because of its long record and benefits over other available indices, the AA index is used as a measure of geomagnetic activity throughout this study.

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[10] http://www.ngdc.noaa.gov/STP/SOLAR_DATA/RELATED_INDICES/AA_INDEX/

[11] ftp://ftp/ngdc.gov/STP/SOLAR_DATA/RELATED_INDICES

2.2.6 Superposed Epoch Analysis

This section describes the origin and method of one of the common techniques used in solar-weather studies – superposed epoch analysis. The superposed epoch analysis method was first devised by *Chree (1913)*, who used it to confirm the ~27-day recurrence interval in geomagnetic activity. This relatively simple technique involves three steps and is used to detect a consistent change in one time series (it is convenient to label this as the 'response' time series) in response to an intermittent event in another (best labelled as the 'event' time series). The first step involves the selection of key dates; these correspond to intermittent occurrences in the event time series and in each case are designated as day zero. *Chree (1913)* chose the five days of each month with the highest horizontal magnetic field intensity using data from Kew Observatory. In the next step, corresponding values from the response time series are found for the selected key dates. Note that in *Chree's (1913)* study, the event time series and the response time series are the same; that is, magnetic field intensity. A certain amount of lag is also included to allow for delays between events in one time series influencing the other. Because Chree was examining the ~27 day recurrence interval in geomagnetic activity, values for geomagnetic activity from -5 to +35 days (around the key date) were extracted. In the final step, the intervals extracted from the response time series are lined-up and the values for each lag are averaged. The assumption behind superposed epoch analysis is that random fluctuations are averaged out, whereas a consistent response relative to the key date is preserved by the averaging process (*Haurwitz and Brier, 1981*).

The results of Chree's superposed epoch analysis are shown in Figure 2.16. The recurrence of high geomagnetic activity roughly 27 days after the key dates is evident. It is now known that this is due to the rotation of the sun, which has a 27-day period[12]. Because of the success of this simple, yet powerful, technique it is now a common tool

[12] The 27-day period of solar rotation is actually an average between the 24-day period at the solar equator and the 30-day period at the solar poles (*Hathaway, 1998*). The 27-day cycle in geomagnetic activity is due to the presence of open coronal holes on the solar surface, which have been described in section 2.2.2.

in geophysics (*Lam and Samson, 1994*). It is also commonly used in sun-weather studies that focus on daily timescales (see, for instance, *Tinsley et al., 1989; Pudovkin and Babushkina, 1992a; Stening, 1994; Kirkland et al., 1996; Pudovkin and Veretenenko, 1996; Besprozvannaya et al., 1997; Pudovkin et al., 1997; Veretenenko and Pudovkin, 1997; Egorova et al., 2000; Gabis and Troshichev, 2000; Wilcox et al., 1973*). Chapter four will show, however, that sometimes it is of limited practical use in atmospheric science because of the amount of 'noise' inherent to meteorological time series, and that many of the results obtained using this method are questionable.

2.2.7 Early approaches

Stagg (1931) was one of the first to attempt to link geomagnetic activity to meteorological variations. He compared geomagnetic data (not the AA index, however), to hourly atmospheric pressure data from Aberdeen Observatory[13]. While conceding that no connection between the two geophysical parameters was evident when daily mean data were used, Stagg reported an 'unsuspected' relationship when using hourly data. He averaged hourly atmospheric pressure into two categories based on geomagnetic conditions. In a process reminiscent of the superposed epoch analysis method developed by *Chree (1913)*, Stagg used five 'quiet' and five 'disturbed' days in each month, and averaged atmospheric pressure for these days for each hour. In the resulting averages, he noted that the forenoon maximum in atmospheric pressure (occurring at 10-12 hours GMT) was relatively less during disturbed conditions. The opposite occurred at the evening maximum (20-24 hours GMT), with atmospheric pressure higher, on average, during geomagnetically disturbed conditions than quiet conditions. He also noted that this relationship was dependent on the level of solar activity; the relationship was most evident during low solar activity and lacking during high solar activity.

Despite the curious relationship that *Stagg (1931)* described, very little modern research has been done along these lines since then. Numerous studies have addressed links

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[13] Now known as Cromwell Tower; see http://www.abdn.ac.uk/physics/astro/cto/histcromwell2.htm

between geomagnetic activity and the atmosphere (these are examined in section 2.3), but none have used hourly data and very few incorporate both geomagnetic and solar activity. Appendix A, therefore, describes a brief analysis of the relationship described in *Stagg (1931)* using modern data. Six-hourly atmospheric pressure data recorded at Aberdeen (kindly provided by Graham Bartlett, from the UK Meteorological Office) were analysed in a method similar to that described in Stagg's paper. The data begin in 1921 (the same as Stagg's study) and continue to 1995. Stagg's results are visually striking, yet the analyses in Appendix A find no such relationship in the updated data, which include data for the same period as Stagg's study. Despite a number of mitigating factors relating to the methods and data used in the analyses (see Appendix A for more details), the disparity between Stagg's results and those presented here is an example of how controversial and subjective the field of solar-climate research can be. The relationship between geomagnetic activity and climate (and weather) is the focus of this thesis and is therefore discussed separately in section 2.3, which describes some other inconsistencies and points for further consideration in this field of study.

In 1934, Brooks published on the link between sunspots and thunderstorm frequency. Brooks expanded on the earlier results using a more global distribution of thunderstorm records (Figure 2.17). Like *Stagg's (1931)* research, Brooks' paper exemplifies the bold, optimistic views of some of the early climate researchers, which perhaps in today's sceptical environment would not be well received. His results are shown in Table 2.2. Notable correlations are evident for Siberia, Sweden, the West Indies, and Southern Asia.

The important aspect of this paper is not only the possible solar-climate link it describes involving thunderstorms but the fact that it exemplifies how a lot of solar-climate research is based on assumptions and speculation and do not address specific climatic problems. Brooks suggested that there may be an *a priori* reason for linking thunderstorms to sunspot numbers because of their "affinities with the upper air as well as the with the surface" (*Brooks, 1934*; page 153). His paper, however, predates the discovery of the Forbush decrease and the revelation that solar modulated cosmic rays influence atmosphere ionisation (see later sections). The *a priori* reasoning, therefore, is particularly limited because no physical mechanism linking the sunspots and thunderstorms had been previously suggested. Furthermore, Brooks' study, while useful and of scientific interest, does not address any specific problems relating to thunderstorm activity.

2.2.8 Cosmic Rays and Clouds

Solar-climate relationships are often criticised due to the lack of proven physical mechanisms through which solar variability can influence climate. The suggestion that cosmic rays influence cloud formation, however, is one possible mechanism that has remained in favour with some researchers since its inception in the 1950s.

Section 2.2.3 described how solar-modulated geomagnetic activity influences the cosmic-ray flux into the earth's atmosphere through the 'Forbush decrease'. Shortly after the description of this phenomenon by Forbush in 1954, *Ney (1959)* described another relationship between cosmic ray flux and atmospheric ionisation in the troposphere and stratosphere. Figure 2.18 shows the changes in atmospheric ionisation for various geopotential heights between 1954 (solar maximum) and 1957 (solar minimum). It demonstrates that even at the surface, changes of ~4% occur over the solar cycle, while at the 10 hPa geopotential level the changes exceed 50% at the poles. Larger variations in cosmic-ray flux are evident at the poles because the amount of 'blocking' of cosmic rays mainly depends on the horizontal intensity of the earth's magnetic field. Recalling Figure 2.3, it is evident that at the earth's equator the horizontal component of the magnetic field is at a maximum, while at the poles it is minimal.

Ney (1959) presented a diagram that showed a speculative chain-of-events whereby solar activity influenced atmospheric temperature via cosmic rays and ionisation. This diagram has been reproduced in Figure 2.19, and marks the inception of one of the more popular solar-climate mechanisms. Ney's speculative mechanism was augmented by *Dickinson (1975)*, who incorporated the role of stratospheric aerosols in the cosmic-ray modulation of cloud formation. Dickinson argued that although it is known that ions assist homogeneous water vapour nucleation at lower supersaturation levels, the high levels of supersaturation required for ions to make a difference do not occur in the troposphere because of the abundance of particles for heterogenous nucleation. Instead, Dickinson speculated that varying amounts of atmospheric ionisation, associated with cosmic rays, could modulate the formation of sulphate aerosols. These, in turn, can act as cloud condensation nuclei.

The cosmic-ray flux/cloud hypothesis was further developed in a series of papers by Brian Tinsley and co-workers (*Tinsley et al., 1989; Tinsley and Deen, 1991; Tinsley and Heelis, 1993; Tinsley, 1996a, b*), which describe what is referred to as the 'Tinsley' mechanism by some researchers. This mechanism links cosmic rays to cloud cover through processes involving atmospheric electricity (Figure 2.20, taken from *Tinsley and Deen, 1991*). The process begins with supercooled droplets[14] obtaining a charge through atmospheric ionisation, which *Ney (1959)* has shown is influenced by the cosmic-ray flux. By virtue of their charged state, the supercooled droplets readily combine and grow to sizes that allow freezing. Ice crystals formed in this manner fall to lower levels in the atmosphere, where they glaciate mid-level clouds. The release of latent heat during the glaciation process can intensify cyclones, which can then alter storm tracks and influence gravity waves (*Tinsley and Deen, 1991*). According to this mechanism, climate therefore varies with the state of the global electric circuit, which is modulated by the cosmic-ray flux.

The Tinsley mechanism is one of the more comprehensive solar-climate mechanisms, which *Tinsley et al. (1989)* point out, has the benefit of being applicable to solar-climate relationships of any timescale, including the daily level. Accordingly, it is quite popular with solar-climate researchers. However, the mechanism suffers from uncertainties relating to cloud nucleation and electrofreezing processes. For example, *Detwiler (1993)* points out that the current theories and laboratory observations do not support the view that electrofreezing is an important mechanism for tropospheric cloud formation.

[14] Due to the effect of surface tension, it is possible for water droplets of 5 µm or less to resist homogenous freezing at temperatures down to -40°C (*Rogers and You, 1989*).

In another critical assessment of the cosmic ray/cloud link, *Mohnen (1990)* concluded that "cosmic rays can not have a significant impact on stratospheric aerosol population." (page 1933). Mohnen's objection relates primarily to the limited magnitude of the changes in ion density associated with cosmic rays, which are two orders of magnitude smaller than those associated with volcanic activity. He also states that cosmic ray induced nucleation 'cannot compete' with nucleation on pre-existing particles derived from surface or meteoric origin.

It is evident that the exact method through which the cosmic-ray flux might influence cloud cover is not clear and certainly a point of contention for climate researchers. Despite the continuing refinement and development of the cosmic ray/cloud mechanism for solar-climate relationships, the much-needed 'evidence' supporting these theories was not available until Svensmark and Friis-Christensen published 'Variation of cosmic ray flux and global cloud coverage – a missing link in solar-climate relationships' in 1997. *Svensmark and Friis-Christensen (1997)* analysed smoothed monthly satellite cloud data[15] over the midlatitude oceans between 1983 and 1990. They found that the total cloud cover varies between 3-4% in that period and that these variations are highly correlated to cosmic-ray intensity.

Despite uncertainties regarding the impact that a 3-4% change in cloud cover would have on the earth's climate, by providing evidence for a viable solar-climate mechanism Svensmark and Friis-Christiansen's results could have potentially become a cornerstone on which the credibility of solar-climate relationships could stand. However, there are some important shortcomings in these results, and accordingly, they have not gained general acceptance. *Jørgensen and Hansen (2000)* suggest not only that the observed effects may be explained by the El Niño/Southern Oscillation variations or volcanic activity, but also that *Svensmark and Friis-Christensen's (1997)* findings do not take into account important factors relating to the optical thickness of clouds.

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[15] From the *International Satellite Cloud Cover Program* (ISCCP), which was established in 1982 and ran until June 2002 (see http://isccp.giss.nasa.gov/overview.html).

Another shortcoming of the results is described in *Kernthaler et al. (1999)*, who repeated *Svensmark and Friis-Christensen's (1997)* work but used only data from 1985 to 1988, when cloud satellite measurements are most reliable. They also included data from high latitudes as well as data over land. *Svensmark and Friis-Christensen (1997)* had indicated that the relationships between cloud cover and cosmic rays should be greatest at high latitudes, as that is where variations in ionisation due to cosmic rays should be greatest (recall Figure 2.18 showing atmospheric ionisation data from *Ney, 1959*). However, *Kernthaler et al.* found the opposite – that the inclusion of the high-latitude data reduces the amplitude of the link between cloud cover and cosmic rays, and that there is no correlation between different cloud types and cosmic ray flux.

Similarly, *Kristjánsson and Kristiansen's (2000)* evaluation of the Svensmark/Friis-Christensen results casts doubt over the cosmic ray/cloud relationship. They found that by extending the temporal coverage of the analysis (by incorporating the ISCCP D2 data set) the relationship described in *Svensmark and Friis-Christensen (1997)* is not evident in the data from 1989-1993. They conclude that the strong correlation in the ISCCP C2 dataset used by *Svensmark and Friis-Christiansen (1997)* may be 'purely coincidental'. They do concede, however, that a weak, negative correlation (r = -0.345) is evident between synoptic cloud observations over the oceans[16] (from *Norris, 1999*) and cosmic-ray flux.

An apparent link between cosmic rays and synoptic cloud cover data was also reported by *Veretenenko and Pudovkin (1995)*. They linked changes in synoptic cloud cover to the Forbush decrease of galactic cosmic rays, but examined only day-to-day changes. *Veretenenko and Pudovkin (1995)* examined total cloudiness for the period 1969-1986 for three latitudinal zones (50°N, 60°-64°N, 65°-68°N) within the former U.S.S.R. The data were separated into winter (October through to March) and summer (April to September). The superposed epoch analysis method was used, with Forbush decreases of 3% or more set as key events. Their results show a decrease of 5% to 7.5% in

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[16] *Kristjánsson and Kristiansen (2000)* suggest that the reason the cosmic ray/cloud link is perhaps evident only over the oceans (and only for low clouds) is because of the limited amount of cloud condensation nuclei and the greater cooling effect that occur there.

cloudiness in the latitudinal zone of 60° to 64°N on the first and second day following Forbush decrease events for the winter half-year (Figure 2.21). A similar but smaller response is evident in the summer half-year. For the latitudinal zone of 65° to 68°N, *Veretenenko and Pudovkin (1995)* report an increase in cloudiness (for the winter period only) starting two days before the Forbush decrease, at which point cloudiness returns to the normal value.

Veretenenko and Pudovkin's study examined the day-to-day relationships between cloud cover and cosmic rays. As such, it is fundamentally different to *Svensmark and Friis-Christensen's (1997)* study and its implications for solar-climate relationships are unclear. Although it has not been scrutinised to the same extent as Svensmark and Friis-Christensen's study, Veretenenko and Pudovkin's study appears to support the view expressed in *Tinsley et al. (1989)* that the link between cosmic-rays and clouds should operate at all timescales.

Svensmark and Friis-Christensen expand on their original results and rebut some of the criticisms of their initial work in *Svensmark (1998)*, *Friis-Christensen (2000)*, and *Svensmark and Friis-Christensen (2000)*. For instance, *Friis-Christensen (2000)* and *Svensmark and Friis-Christensen (2000)* indicate that the ISCCP-C2 data that were used by *Kernthaler et al. (1999)* were derived by a poor algorithm, and subsequently provides a different categorisation of cloud types to the ISCCP-D2 data set. *Svensmark and Friis-Christensen (2000)* report that the findings of *Kernthaler et al. (1999)* cannot be reproduced in the newer ISCCP-D2 data set. *Friis-Christensen (2000)* explains that although global cloud cover is correlated to El Niño events, it does not exclude a cosmic ray influence. It is evident, therefore, that the solar forcing of cloud cover remains debatable.

The link between cosmic rays and clouds is contentious on two points. Firstly, the theoretical mechanisms by which cosmic rays influence cloud nucleation are disputed. In fact, both *Kristjánsson and Kristiansen's (2000)* and *Jørgensen and Hansen (2000)* use the fact that there is no known or proven mechanism linking cosmic rays to clouds to criticise the results of *Svensmark and Friis-Christensen (1997)*. Secondly, the observed links between cosmic rays and clouds are questionable.

It is obvious, however, that the main problem is the limited quality and temporal range of the available cloud cover data. Two things must occur before a possible cosmic ray/cloud mechanism can be proven – our understanding of cloud nucleation dynamics and atmospheric aerosols needs to improve, and a longer, better quality data set is required. Nevertheless, the notion that geomagnetic activity can influence climate by modulating cosmic rays remains an interesting possibility in solar-climate research, and a potential solar-climate mechanism that is considered in chapter five.

2.2.9 The Maunder Minimum

In 1976 and 1977, Astronomer John Eddy published two seminal papers that linked long-term solar activity to climate. German astronomer Spörer and the superintendent of Greenwich Observatory, Maunder, were the first to note that the period between 1645 and 1715 was one of very little solar activity *(Eddy, 1976)*. Eddy verified this using ^{14}C and other data, and concluded that during this period, known as the Maunder minimum, "…solar activity all but stopped." (page 1189). He also described a minimum in solar activity between 1460 and 1550, which he termed the Spörer minimum, and an unusually active period in the sun between 1100 and 1250 known as the Grand Maximum[17].

In both papers (*Eddy, 1976, 1977*), Eddy suggested that the changes in long-term solar activity were mirrored by changes in global climate; low solar activity equates to colder climates and glacial advance, while increased solar activity causes warmer climates. *Eddy (1977)* points out that the Maunder and Spörer minima coincide with the two coldest points of the Little Ice Age, while the Grand Maximum coincides with the Medieval Climatic Optimum[18].

[17] *Pang and Yau (2002)* provide a comprehensive description of the reconstruction of historical solar activity from 'ancient' observations and of the behaviour of the sun over the last 1800 years.

[18] The Grand Maximum is also known as the Medieval Maximum, and the Medieval Climatic Optimum is sometimes referred to as the Middle Ages Warm Epoch.

Eddy (1977) estimated that the change in the solar constant associated with the Maunder minimum was 1%; modern estimates are considerably lower. For instance, *Lean et al. (1992)* suggest a change of 0.24%, while *Baliunas and Soon (1995)* suggest an increase in solar irradiance since the Maunder minimum of 0.4%. Despite the limited magnitude of these solar irradiance changes, the coincidence of reduced solar activity and global climate minima remains one of the most compelling links between solar activity and climate. *Eddy (1977)* cautions, however, that the long-term relationship he describes does not necessarily support the extrapolation of these links to the 11-year solar cycle. This long-term relationship is therefore fundamentally different to the modern changes described in the results of this thesis.

2.2.10 The Stratosphere and Solar Activity

Beginning in 1987, Labitzke and van Loon published a number of papers presenting compelling evidence for a link between solar activity and the stratosphere. Their initial papers (*Labitzke, 1987; Labitzke and van Loon, 1988*) described two types of relationships. The first is a link between the northern hemisphere stratospheric polar vortex and solar activity (as represented by the 10.7 cm solar flux), which is modulated by the quasi-biennial oscillation (QBO). The second is a link between 30 hPa geopotential heights throughout the rest of the stratosphere, evident all year round and at a maximum in the summer hemisphere.

Labitzke and van Loon (1988) found that although the 30 hPa geopotential heights over the North Pole in winter were not correlated to the solar flux between 1956 and 1987 (r = 0.14), quite different results were obtained when the data were separated according to the phase of the QBO. The QBO is a stratospheric phenomenon, first observed in 1961, relating to the direction of equatorial zonal winds (*Huesmann and Hitchman, 2001*). The QBO winds change direction (from westerly to easterly and vice versa) roughly every 28 months, and propagate downwards from the top of the stratosphere at a rate of 1 km per month (*Huesmann and Hitchman, 2001*). During the QBO east phase (negative QBO values) the 30 hPa geopotential heights are negatively correlated to the solar flux (r_{max} = -0.45). During the QBO west phase, however, the polar geopotential height data are in phase with the solar cycle, and the correlation coefficient is 0.76.

Furthermore, they observed that similar correlations occur at the 500 hPa level and for sea level pressure values, as well as for 30 hPa temperature data.

In further reviews and refinements of their initial results, *Labitzke and van Loon (1993, 1996)* and *van Loon and Labitzke (1994)* suggested that during solar maximum the sun reverses the roles of the QBO on the stratospheric polar vortex. When early winter (November and December) coincides with the QBO west phase and the solar maximum, the Aleutian high is enhanced and the critical line that divides the easterlies from the westerlies in the stratosphere is displaced north *(van Loon and Labitzke, 1994)*. The resulting northward (and vertical) propagation of quasi-stationary long waves allows for the warming and breakdown of the polar vortex in the following months.

Labitzke and van Loon (1997) also describe another relationship that occurs throughout the whole year and links 30 hPa geopotential heights in the subtropics to the solar cycle. Using *NCEP/NCAR* reanalysis data, *Labitzke and van Loon (1997)* and *van Loon and Labitzke (1999)* found that the correlations occur in both hemispheres and follow the sun. That is, the correlations are greatest in summer. Once again, these correlations are evident in 30 hPa temperatures as well as other levels in the atmosphere (Figure 2.22). Using radiosonde station data, from Hawaii and Truk Island, *Labitzke and van Loon (1999)* explain that during solar maxima the troposphere is warmer and the tropopause colder than during solar minima. This, in part, accounts for the changes in the 30 hPa geopotential heights.

Based on their own results and those of *Kodera et al. (1990)* and *Haigh (1996)*, *Labitzke and van Loon (1993, 1996, 1997)* suggest that the correlations result from solar ultraviolet radiation changes in the upper stratosphere, as well as a solar influence on the Hadley circulation. Based on the location of the highest correlations in each hemisphere, they conclude that “the solar influence is not entirely radiative but that it also affects the poleward transport of ozone”. (*Labitzke and van Loon, 1997*; page 410).

This series of studies (*Labitzke and van Loon, 1988, 1993, 1996, 1997; van Loon and Labitzke, 1994, 1999; Labitzke, 1987*) outlines some of the most comprehensive studies of solar-climate relationships. It also demonstrates that spatial and temporal analyses of solar-climate relationships can be used to deduce, to some extent, the likely mechanisms by which solar activity might influence climate. The relevance of the relationship described in these studies to recent climate change has not yet been described in the literature, but recent studies (for example, *Baldwin and Dunkerton, 2001; Black, 2002*) indicate that the stratosphere has a significant influence on the troposphere. It is therefore likely that the stratosphere plays an important part in both solar-climate relationships and recent climate change.

Chapter five, which considers solar-climate mechanisms, examines the role of the stratosphere in geomagnetic activity-atmospheric circulation relationships. Appendix E compares the geomagnetic activity signature in the stratosphere to that of the solar cycle described in *van Loon and Labitzke (1999)*, and demonstrates that they are fundamentally different.

2.2.11 Solar-cycle Length and Climate

The first link between solar-cycle length and climate was reported in *Friis-Christensen and Lassen (1991)*. *Friis-Christensen and Lassen (1991)* found that links between surface air temperature and solar activity were not credible if sunspot number was used as an index for the latter. This is because changes in the sunspot number lag behind changes in air temperature. They suggested, however, that there was no *a priori* reason to believe that solar activity was perfectly represented by the sunspot number, and instead claimed that the length of the solar cycle was a better index of solar activity; long cycles are associated with lower levels of solar activity, while shorter cycles are indicative of increased solar activity.

Friis-Christensen and Lassen (1991) determined the length of the solar cycle using a weighted (12221) filter applied to individual solar-cycle minima and maxima epochs of the sunspot number. The use of the smoothed solar-cycle length instead of the sunspot number removes the apparent lag of solar activity to surface temperatures, and leads to a striking similarity between northern hemisphere land temperature and solar activity from 1860 onwards (Figure 2.23). The similarities between the two include an upward trend from 1900-1940 and from 1970 onwards, and a downward trend between 1945 and 1970. Because instrumental temperature records only extended back to 1851, but sunspot data were available from 1715 onwards, Friis-Christensen and Lassen extended their comparison using North Atlantic sea ice data. Using a 22-year running mean index of sea ice data, which covered the same time period as the smoothed solar cycle record, they found that maxima in solar activity in 1770, 1850, and 1940 correspond to minima in sea ice near Iceland.

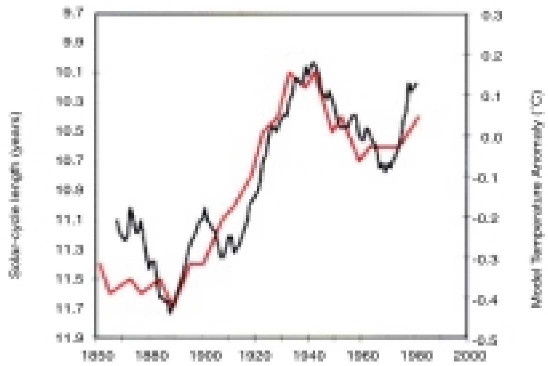

Figure 2.23. Solar cycle length (red line) and average temperature anomalies (from *Friis-Christensen and Lassen, 1991*). This image was obtained and modified from http://web.dmi.dk/fsweb/solarterrestrial/sunclimate/welcome.shtml. It demonstrates the striking visual resemblance between the solar cycle length and terrestrial temperature.

From these similarities, they concluded that the relative importance of greenhouse gases might be less than previously anticipated. They also suggested that because of the link between smoothed solar-cycle length and long-term changes in land air temperature, solar-cycle length can possibly be used as an index of solar energy output.

Based on the results of climate modelling, *Kelly and Wigley (1992)* disagreed slightly with *Friis-Christensen and Lassen's (1991)* results. They concluded that while a combination of solar-cycle length forcing and greenhouse warming is evident in temperature records, the latter is the dominant factor in the recent warming trend.

Unperturbed, *Friis-Christensen (1993)* extended his analysis to include global land temperature data. He reported that the temperature curve is changed by only a minor amount with the inclusion of southern hemisphere data (and presumably the relationship to solar-cycle length remains the same). The inclusion of ocean temperatures into the global temperature data set, however, introduced a 'marked delay' in the response of the temperature curve to the solar-cycle length data. *Friis-Christensen (1993)* explains that this is due to the thermal inertia of the oceans. Friis-Christensen's expansion of the results to include a global data set is a significant advancement on the original relationship, but it typifies the approach that many solar-climate researchers have to the southern hemisphere. *Friis-Christensen (1993)* did not specifically describe the link between solar-cycle length and southern hemisphere land temperatures. This is unfortunate, because the differences (as well as the similarities) between the responses of the two hemispheres to solar forcing could be a useful tool for the validation of solar-climate links and the deduction of mechanisms.

The results of *Hameed and Gong (1994)*, who examined the solar-cycle length/climate relationship at a regional level, supported the initial results of *Friis-Christensen and Lassen (1991)*. *Hameed and Gong (1994)* expanded on earlier results by comparing solar-cycle length to springtime climate in the Yangtze River valley. They argued that if solar-cycle length was indeed an indicator of solar output, then the solar influence on climate should be felt in specific regions over the world, and not just the overall northern hemisphere land temperature. They used the timing of blossoming and leafing plants, recorded in Chinese documents since the 16th century and considered reliable indicators of changes in spring temperature, as a climate record of the lower and middle Yangtze River valley. They supplemented this data with records of the last date of snowfall. The climate records overlap the smoothed solar-cycle length data from 1740 onwards. The similarity between the two series prompted *Hameed and Gong (1994)* to suggest that there is a relationship between solar-cycle length and spring temperatures in the Yangtze River valley over this period. A link between solar-cycle length and regional temperature (Figure 2.24) was also described in *Butler (1994)*, who examined maximum, minimum, and mean temperatures at Armagh Observatory (Ireland). Butler concluded that solar activity, as represented by the solar-cycle length, "has been a dominant influence on the temperature of the lower atmosphere in the northern hemisphere over the past 149 years" (page 41).

The link between solar-cycle length and northern hemisphere land temperature was given further credibility with the research of *Lassen and Friis-Christensen (1995),* which examined the relationship over the past five centuries. *Lassen and Friis-Christensen (1995)* argued that given the lack of a physical mechanism that could account for the links between solar-cycle length and climate, statistical methods alone would be hard-pressed to provide new results in this matter. Therefore, as a means of further testing the validity of their previous results they increased the temporal coverage of their study. Using sightings of low-latitude auroral displays as a proxy for sunspot data and temperature data from *Groveman and Landsberg (1979)*, they extended their comparison of solar-cycle length and northern hemisphere land temperature back to 1579. They found that their results confirmed those of *Friis-Christensen and Lassen (1991)*. It was at the very end of this paper that they raised the possibility that the mechanism behind the solar-cycle length and climate link may not, in fact, be related to solar irradiance, but could instead be due to energetic particles (refer to section 2.2.3).

The results of *Baliunas and Soon (1995)*, however, provided evidence that reinforced the view that links between solar-cycle length and terrestrial temperature are due to solar irradiance changes. They compared the chromospheric emission fluxes of 18 solar-type stars[19] to cycle length. They found that a positive correlation between brightness and activity is evident for all the solar-type stars and conclude that cycle amplitude, as well as the average level of activity, increases during shorter cycles. This supports the earlier assumption of some solar-climate researchers that the solar-cycle length can operate as a proxy for solar irradiance. *Baliunas and Soon (1995)* explain, however, that the chromospheric emission fluxes that they report are also a proxy of surface magnetic fields, which *Lockwood (2001)* indicated is manifested in the terrestrial geomagnetic AA index. This means that the solar cycle length may be related to cosmic ray flux (through the Forbush decrease) and/or geomagnetic activity, as well as solar irradiance. Therefore, there are a number of possible mechanisms linking solar-cycle length to northern hemisphere land temperature.

Further confirmation of the temporal stability of the solar-cycle length-climate relationship was found in the results of *Zhou and Butler (1998)*. Using tree-ring index data from the International Tree-Ring Data Bank[20], they compared tree-ring widths to solar-cycle lengths for 69 datasets spanning over 594 years. In some cases, the length of

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[19] Stars that are close in mass and age to the sun and show cyclic behaviour comparable to the 11-year solar cycle.

[20] Accessible through the *International Tree Ring Data Bank* at the *Geophysical Data Center* (Boulder, Colorado), http://www.ngdc.noaa.gov/paleo/treering.html

the tree-ring index reaches back in excess of 2000 years. Another significant aspect of this data set is that although the vast majority of records are from North America, there are a small number of records in the southern hemisphere from countries such as Argentina, Chile, New Zealand, and Australia. *Zhou and Butler (1998)* used a Monte Carlo test method to determine that despite the generally low correlations, most (59 of the 69) of the tree-ring widths were significantly correlated to the solar-cycle length. The significant correlations include those of the southern hemisphere tree-ring width indices.

In 1998 and 1999, a number of papers were published examining the accuracy and validity of *Friis-Christensen and Lassen's (1991)* calculation of the solar-cycle length index. *Mursula and Ulich (1998)* published a new method for determining the solar-cycle length. Their 'median based definition' of the solar-cycle length reduces the inaccuracy of length estimates from months to days. The long-term solar-cycle length differs very little to the one used in *Friis-Christensen and Lassen (1991)*, however, and so the long-term relationship between solar-cycle length and climate remains unchanged. In *Fligge et al. (1999),* a 'more objective' method of calculating solar-cycle length is presented, which involves the use of the continuous wavelet[21] transform. *Fligge et al. (1999)* found that despite using a number of different solar activity indicators, their objective determination of solar-cycle length generally agrees with that originally presented in *Friis-Christensen and Lassen (1991)*.

Although these papers verified the original methods use to calculate the solar cycle length, some of the other aspects of the solar-cycle length/climate relationships did not bear scrutiny as well. *Laut and Gundermann (1998a)* dispelled any notion that solar activity alone could explain the recent warming of global temperatures. Despite the visually strong relationship between the 11-year running mean of northern hemisphere land temperature and solar-cycle length evident in the literature, Laut and Gundermann found that a similar relationship can be achieved by adding artificial trends to the

[21] An overview of the use of wavelets in atmospheric sciences can be found in *Torrence and Compo (1998).*

temperature data. They conclude that the relationship outlined in *Friis-Christensen and Lassen (1991)* cannot be used to rule out a greenhouse contribution to global temperatures during the last 140 years.

Laut and Gundermann (1998b) went a step further and declared that the link between solar-cycle length and northern hemisphere temperature appears to support the hypothesis of greenhouse warming. They found that the relationship between solar-cycle length and temperature is strengthened when they remove the assumed impact of greenhouse warming from the northern hemisphere temperature record, and therefore conclude that solar activity alone cannot account for the recent long-term changes in northern hemisphere temperatures.

Thejll and Lassen (2000), in updating the solar cycle and northern hemisphere temperature relationship using data from the 1990s, found that the long-term temperature record is no longer dominated by solar activity. They found that the correlation between solar cycle length and northern hemisphere temperature is somewhat reduced when another decade of data from the 1990s are included (r is reduced from -0.82 to -0.76); the results are no longer significant at the 95% confidence level (as determined with the use of Monte Carlo simulations). *Thejll and Lassen (2000)* also add that the residuals from the solar-cycle length and northern hemisphere temperature correlations show an upward trend since 1970. The view that greenhouse forcing is the dominant factor in recent climate change, rather than solar activity (as represented by solar-cycle length), is also presented in *Damon and Presitykh (1999)* and *Marcus et al. (1999)*.

When *Laut and Gundermann (2000)* updated the relationship outlined in *Friis-Christensen and Lassen (1991)* by using the northern hemisphere temperature record from 1400-1980 of *Mann et al. (1998)* combined with modern data from the Hadley Centre[22], they found that the correlation was weak. This prompted them to re-evaluate

[22] Combined land, air and sea surface temperature anomalies for the northern hemisphere 1951-1998. (http://www.meto.gov.uk/sec5/CR_div/Tempertr/lsst_vals.nh.html).

Friis-Christensen and Lassen's (1991) original findings; their conclusions were very unfavourable and suggest that the 'strikingly good agreement' presented in earlier papers is misleading and largely the result of the "unacceptable mixing of (12221)-filtered and nonfiltered data into a single curve" (*Laut and Gundermann, 2000*; page 27,492). *Lassen and Friis-Christensen's (2000)* reply outlines some of the differences in the way the data were treated by *Laut and Gundermann (2000)*, which may explain the conflicting results between the two studies. These include the temperature data and time intervals used, which differed between the two studies, and the fact that *Lassen and Friis-Christensen (2000)* used both sunspot minima and maxima in their calculations, while *Laut and Gundermann (2000)* use only minima.

Reichel et al.[23] *(2001)* turned to econometric techniques to support their solar-cycle length/temperature relationship. They used 'Granger causality testing', a technique sometimes used in econometrics, to show that the solar-climate relationships described in *Friis-Christensen and Lassen (1991)* had the right cause-and-effect ordering[24]. They point out that although this does not validate the physical relationship in question, the possible failure of the Granger causality test would have convincingly negated it.

The relationship between solar-cycle length and northern hemisphere temperature is one of the most suggestive, and also controversial, solar-climate relationships in the modern literature. On one hand, the relationship appears to be robust – it is evident in a variety of data sets, over extended periods of time, and to some extent on regional and hemispheric scales. Conversely, it is statistically questionable – researchers rarely quantify correlations, do not take into account the serial correlation within the two smoothed time series, and have not considered the practical significance of the results. The main problem, however, relates to the meaning of the solar-cycle length index. While it is generally accepted as a proxy for solar activity, it is not clear which solar phenomenon it represents. The remainder of this section therefore presents analyses that

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[23] Reichel's co-authors are Thejll and Lassen.

[24] Another notable instance where Granger causality testing was used in climate studies appears in *Stern and Kaufmann (1999)*, who used it to confirm the presence of an anthropogenic signal in recent climate change.

examine the potential role of geomagnetic activity in solar-cycle length relationships and the statistical aspects of such relationships.

Lassen and Friis-Christensen (1995) suggested that the similarities between solar-cycle length and northern hemisphere land temperatures might occur because of the influence of cosmic rays. If so, then geomagnetic activity should also be correlated to northern hemisphere land temperatures. This has been demonstrated, to some extent, by *Cliver et al. (1998)*. It has not been proven, however, that the solar-cycle length is a viable proxy for geomagnetic activity, nor has it been determined which of the two indices (solar-cycle length, geomagnetic activity) is better correlated to surface temperatures. This section compares solar-cycle length data used in *Thejll and Lassen (2000)*, provided by Peter Thejll at http://web.dmi.dk/fsweb/soljord/solklima/scl.txt, to the geomagnetic AA index. Details of the solar-cycle length data (derivation methods and discussion) are provided in *Friis-Christensen and Lassen (1991)*, *Lassen and Friis-Christensen (1995)*, and *Thejll and Lassen (2000)*.

Table 2.3 shows the solar-cycle length values and the central years from 1873 onwards for solar cycle minima. It also shows geomagnetic activity values for each central year. Three versions of the solar-cycle length data are shown – the original, unfiltered version (L), and two versions created by Thejll using weighted filters, (L121, representing a 1-2-1 filter) and (L12221, representing a 1-2-2-2-1 filter). Three versions of geomagnetic AA index values are also given for each central year, derived here using the same filters as the solar-cycle length data. Correlation coefficients between the solar-cycle length minima data and the corresponding AA index data are as follows: r = -0.43 between the unfiltered data (N = 12), r = -0.64 for the 121-filtered data (N = 12), and r = -0.65 for the 12221-filtered data (N = 11). The correlations are statistically significant, at the 95% confidence level, for the filtered data only. More importantly, however, the limited magnitude of the correlations does not suggest that geomagnetic activity and solar-cycle length data are readily interchangeable. Correlations for solar-cycle length data for maxima (shown in Table 2.4), show a similar pattern: r = -0.46 for the unfiltered data (N = 11), r = -0.63 for the 121-filtered data (N = 11), and r = -0.70 for the 12221-filtered data (N = 11). Once again, only the correlations using filtered data are statistically significant at the 95% confidence level, and are not high enough to suggest that solar-cycle length data is an accurate proxy for geomagnetic activity. It is not clear, however, whether the large amount of smoothing of the temperature data, used in the solar-cycle length studies, means that the differences between the solar-cycle length index and the geomagnetic AA index will be negligible.

Table 2.3. Solar-cycle length between sunspot minima, cycle central years, and corresponding AA index values. The solar-cycle length data were provided by Peter Thejll. Correlation coefficients between the unfiltered, 121-filtered, and 12221-filtered solar-cycle and geomagnetic data are -0.43, -0.64, and -0.65, respectively. Although the AA index is generally higher during shorter solar cycles the relationship is not strong enough to allow the solar-cycle length and AA indices to be used interchangeably.

Solar cycle data for minima					**Geomagnetic AA index**		
Epoch	L	L121	L12221	Central Year	Unfiltered	121	12221
1878.9	11.70	11.30	11.50	1873.05	20.20	19.65	18.66
1889.6	10.70	11.30	11.50	1884.25	14.10	15.28	17.19
1901.7	12.10	11.70	11.40	1895.65	17.90	16.85	16.85
1913.6	11.90	11.50	11.10	1907.65	17.00	16.78	16.26
1923.6	10.00	10.50	10.80	1918.6	22.40	20.95	19.69
1933.8	10.20	10.20	10.40	1928.7	19.30	21.18	20.51
1944.2	10.40	10.30	10.20	1939	23.20	23.35	23.01
1954.2	10.00	10.30	10.50	1949.2	21.10	22.28	23.73
1964.9	10.70	10.80	10.70	1959.55	32.80	29.50	27.51
1976.5	11.60	11.10	10.65	1970.7	20.00	20.10	20.93
1986.8	10.30	10.55	10.63	1981.65	33.70	30.38	27.86
1996.8	10.00	10.20		1991.8	27.30	28.58	28.75

Table 2.4. Solar-cycle length between sunspot maxima, cycle central years, and corresponding AA index values. The solar-cycle length data were provided by Peter Thejll. Correlation coefficients between the unfiltered, 121-filtered, and 12221-filtered solar-cycle and geomagnetic data are -0.46, -0.63, and -0.70, respectively. Although the AA index is generally higher during shorter solar cycles the relationship is not strong enough to allow the solar-cycle length and AA indices to be used interchangeably.

Solar cycle data for maxima					**Geomagnetic AA index**		
Epoch	L	L121	L12221	Central Year	Unfiltered	121	12221
1883.9	13.30	11.80	11.60	1877.25	8.90	8.63	8.68
1894.1	10.20	11.65	11.70	1889	12.50	12.78	13.83
1907	12.90	11.65	11.40	1900.55	6.00	6.50	8.13
1917.6	10.60	11.20	11.00	1912.3	8.80	10.50	11.85
1928.4	10.80	10.30	10.50	1923	10.20	12.30	13.44

1937.4	9.00	9.70	10.10	1932.9	16.20	16.18	16.16
1947.5	10.10	9.90	10.10	1942.45	21.70	23.50	23.23
1957.9	10.40	10.50	10.40	1952.7	22.10	22.30	22.54
1968.9	11.00	10.85	10.58	1963.4	21.20	20.23	19.46
1979.9	11.00	10.70	10.56	1974.4	30.30	27.75	25.51
1989.6	9.70	10.27	10.59	1984.75	22.50	23.68	24.10

The question now is which index matches temperature records best? Global and hemispheric temperature anomalies, spanning 1856 to 2000, were obtained from the *Carbon Dioxide Information Analysis Center* web page[25] and are from *Jones et al. (2001)*. The anomalies are relative to the 1961-1990 average (*Jones et al., 2001*), and are an updated version of the data used in *Thejll and Lassen (2000)*. The temperature data were compared to the geomagnetic AA index and the magnitude of the correlations was compared to the results presented in *Thejll and Lassen (2000)*. Figure 2.25 compares the annual geomagnetic AA index to annual global and hemispheric temperature data. Both the geomagnetic and temperature data have been smoothed using an 11-point moving average in order to focus on long-term changes and to match the smoothing used in many solar-cycle length studies as well as the use of decadal averages in *Cliver et al. (1998)*. In order to highlight temporal patterns, an 11-point sliding correlation is also shown for each temperature curve.

Figure 2.25 reveals that the application of the 11-point moving average to the temperature and geomagnetic data has severely reduced the variability in these datasets. The original number of observations is 122 but, because of serial correlation, the effective number of observations[26] equals one for all three correlations. Therefore, the correlation coefficients between geomagnetic activity and global (r = 0.90), southern hemisphere (r = 0.89), and northern hemisphere (r = 0.88) temperatures are not

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[25] http://cdiac.esd.ornl.gov/trends/temp/jonescru/jones.html

[26] The effective number of observations was calculated using the formula of *Slonosky et al. (2000)* and is described in chapter three

statistically significant at the 95% confidence level[27]. More importantly, the initial visual similarity of the indices fades with closer scrutiny. It is evident that maxima and minima in the temperature indices do not match the corresponding extrema in the AA index. There is some indication of a lagged relationship, operating over roughly 10 years. Note, for example, the minimum in the AA index around 1900, which is followed by a minimum in temperature anomalies around 1910. Similarly, a minimum in the AA index around 1965 is followed by a minimum in northern hemisphere temperature anomalies around 1975. There is, however, no plausible explanation for a relationship operating over such an extreme lag interval and when coupled with the inconsistent temporal nature of the correlations (also shown in Figure 2.25) it is not possible to conclude that geomagnetic activity influences surface temperature. At the same time, it is difficult to dismiss such a relationship entirely because of the striking visual resemblance.

One point that is clear, however, is that the techniques used in *Thejll and Lassen (2000)* and their predecessors, as well as *Cliver et al. (1998)*, may be over-representing the similarity between geomagnetic and temperature indices. By under-sampling either temperature or solar indices, their analyses have essentially smoothed the phase of the data, as well as the magnitude of the variations. *Thejll and Lassen (2000)* typically average 11 years of temperature data around the central years of solar cycle extrema. Conversely, *Cliver et al. (1998)* extracted decadal averages of geomagnetic activity corresponding to the five-year intervals of temperature data they used. In both cases, much of the phase of the data is lost in the averages, not only because of the smoothing process but also because the continuous solar and temperature indices are only sampled at intervals. This is particularly pertinent to the findings of *Friis-Christensen and Lassen (1991)* – the first of the solar-cycle length studies. Their impetus for using the solar-cycle length, instead of the sunspot number, was that surface temperatures and sunspot numbers were out of phase (temperature variations led sunspot variations). When *Friis-Christensen and Lassen (1991)*, and other researchers that used the solar-

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[27] They are, however, slightly greater than the corresponding solar-cycle length correlations presented in *Thejll and Lassen (2000)*.

cycle length index, found that the length of solar cycles was more similar to temperature records than sunspot numbers they assumed that it was because the solar-cycle index was a more accurate measure of solar activity. It can be argued, though, that the improved relationship when solar-cycle length or geomagnetic activity is used instead of sunspot numbers is statistical in nature, despite the physical basis for such an improvement. This is demonstrated in Figures 2.26a and 2.26b, and is supported by the fact that, as yet, there is no solar process that has unambiguously been associated with solar-cycle length, though solar irradiance changes remain the most likely process.

Figure 2.26a depicts sunspot number values and global temperature anomalies; the data are displayed for solar minima only. A 12221 filter was applied to the sunspot index in the same manner as some solar-cycle length studies (for example, *Friis-Christensen and Lassen, 1991*) and solar minima years and values were extracted from the smoothed sunspot index. Corresponding temperature values were derived by averaging 11 years of temperature data centred on the solar minima years. Therefore, the technique used to modify the data in Figure 2.26a is somewhat similar to that employed by *Thejll and Lassen (2000)* and *Cliver et al. (1998)*. The important difference, however, is that this technique does not consider solar-cycle length at all – instead it simply samples the sunspot record only at solar minima. The strong visual resemblance between the two time series proves that the strengthening of the solar-climate relationship when the solar-cycle length is used instead of the sunspot number (as in *Friis-Christensen and Lassen, 1991*) does not occur solely because solar-cycle length is a more appropriate measure of solar activity. Instead, it indicates that the improved results are partly a consequence of the smoothing process employed and the under-sampling of both solar and temperature indices. The correlation coefficient between the solar minima sunspot averages and the corresponding global temperature averages is 0.73. A similar resemblance between the sunspot number and global temperature is depicted in Figure 2.26b, which shows sunspot maxima values. The correlation coefficient between the solar maxima sunspot averages and the corresponding global temperature averages is 0.80. The magnitude of these correlations is roughly equivalent to the corresponding correlation presented in *Thejll and Lassen (2000)*, which extends to 1999 (r = -0.76) when the temperature data are sampled as discrete 11-year averages. This indicates that some of the strong resemblance between indices of solar-cycle length and long-term averages of terrestrial temperature may be due to the statistical methods employed, and not physical processes reflected in solar-cycle length indices.

The analyses so far have shown that the solar-cycle length index is not a strong proxy for geomagnetic activity, and furthermore that techniques used in the literature to compare both of these indices to annual surface temperature may be overestimating the magnitude of the relationship. It seems that geomagnetic activity correlates better to global temperature than the solar-cycle length. This conclusion is based on the fact that the magnitude of the geomagnetic activity/temperature correlations is greater than the corresponding solar-cycle length temperature correlations detailed in *Thejll and Lassen (2000)*, and that the analyses utilising geomagnetic activity use the entire record rather than just a small subset of the available data. Three points have been elucidated regarding solar-cycle length studies from the analyses presented here:

1. The sampling method used in solar-cycle length studies overestimates the magnitude of the similarities between temperature and solar-cycle length,

2. Geomagnetic activity is not a strong proxy for solar-cycle length, indicating that cosmic-ray flux is not a likely forcing mechanism in solar-cycle length studies,

3. The magnitude of long-term temperature correlations with geomagnetic activity is similar to that of temperature correlations with solar-cycle length data, making the actual solar processes that influence long-term temperature ambiguous.

2.2.12 Prediction

It is evident, from the criticisms of *Pittock (1979)* and the continual scepticism and controversy surrounding solar-climate relationships, that the successful prediction of climate changes based on solar activity remains one of the achievements that will perhaps redeem this sometimes dubious field. Consequently, it is surprising that very few studies consider the predictive value of their results. Furthermore, a search of the literature will reveal that apart from popular science articles, such as *Gribbin's (1987)* anecdotal accounts of Goesta Wollin's suggestion that short-term changes in geomagnetic activity precede severe storms, the use of solar-climate relationships for long (or short) range prediction is practically non-existent.

One exception is found in *Wheeler (2001)*. In this paper, Wheeler evaluates the long-range forecasts by a British company, *Weather Action*[28], which employ the solar-weather technique of forecasting. The actual technique employed for forecasting is kept secret by the company's founder and managing director, Piers Corbyn, but *Wheeler (2001)* reports that it is based on changes in the solar wind and geomagnetic activity.

In *Wheeler's (2001)* evaluation of *Weather Action's* prediction of gales for October 1995-1997, he concluded that "the results provide little evidence to dismiss the observed success rates as being attributable to chance or good fortune." (page 33). He also reported that *Weather Action* successfully forecast the four largest storms of the survey period, a number of months before they occurred! In light of this finding, it appears that the study of solar-climate relationships is a worthwhile enterprise, and that prediction is feasible. There are, however, very few publications relating to the prediction of short- or long-term climate based on solar activity. Wheeler's study is very preliminary, but it suggests that solar-climate relationships may have tremendous potential for long-range weather forecasting. The predictive value of the geomagnetic forcing of atmospheric circulation is examined in chapter five.

2.2.13 Criticism

Perhaps the earliest criticism of solar-climate relationships came very shortly after William Herschel first proposed his theory 1801. It was published in the *Edinburgh Review*, where Lord Henry Brougham referred to Herschel's theory as 'hasty and erroneous' and as a 'grand absurdity'. He wrote, "Since the publication of Gulliver's voyage to Laputa, nothing so ridiculous has ever been offered to the world." (*Brougham, 1803*; page 431). While solar-climate relationships have encountered stiff

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[28] An interesting overview of *Weather Action* and the technique it employs is available online at http://www.firstscience.com/site/articles/corbyn.asp.

criticism in many instances since then, it is safe to say that few have been as enthusiastic as Brougham's. Nevertheless, solar-climate relationships have been criticised on a number of fronts, the most common being poor statistical treatment of the data, the lack of physical mechanisms that could account for the proposed relationships, and the limited practical use of the observed relationships.

Previous sections have already described some of the more focused criticisms against specific aspects of solar-climate relationships (such as the criticism of Tinsley's electrofreezing mechanism, or the dubious nature of the solar-cycle length and northern hemisphere land temperature similarities). This section reviews a selection of general solar-climate criticisms in order to highlight the common arguments against solar-climate relationships, and to reveal some of the shortcomings of the methods used within the field.

The most comprehensive work on this topic is in a number of papers by *Pittock (1978, 1979, 1983)*. At a *Symposium/Workshop on Solar-Terrestrial Influences on Weather and Climate*, held at the Ohio State University in 1978, Pittock presented some criticisms *(Pittock, 1979)* that can also be found in *Pittock (1978)*. Of course, solar-climate studies have progressed a great deal since 1979, but many of his criticisms are still applicable to solar-climate research today. His criticisms from these two papers are discussed here.

The practical significance (that is, the usefulness), of solar-climate relationships is questionable. *Pittock's (1978)* benchmark is long-range climate forecasting. Because many solar climate relationships are not constant in time, or the mechanism by which they operate is not fully understood, the application of solar-climate studies to long-term forecasting is questionable. This is further compounded by the nature of solar-climate studies that only focus on long-term climate changes. Accordingly, they are limited to studying only a small portion of the total variance in a climatic time series *(Pittock, 1979)*. *Pittock (1978)* also pointed out that the usefulness of solar-climate relationships for long-term forecasting is dependent on the forecasting skill for the solar cycle, which (at least at that time) was quite limited.

Pittock (1978, 1979) also raised a number of concerns regarding the statistical aspect of solar-climate relationships. These include data quality (such as homogeneity), spatial and serial correlation and their impact on statistical significance (especially in smoothed data), and data selection (including the conscious or unconscious selection of results, so that only favourable results are pursued).

Pittock (1978) emphasised the need for plausible and testable physical mechanisms, especially because of the limited magnitude of most solar-cycle relationships and the limited number of solar cycles for which the relationships had been observed. *Dessler (1975)* also expressed concern about the lack of theoretical mechanisms that could explain the many solar-climate links that had been expounded in the literature.

Pittock (1978, 1979) concluded with some 'guidelines' for authors, editors, referees, and readers of solar-climate relationships. These are listed here below (in verbatim) and used as a 'benchmark' for results of this thesis in later sections:

1. Understand the properties of the data, their errors, biases, scatter, autocorrelation, spatial coherence, frequency distribution, and stationarity

2. Choose statistical methods appropriate to both the properties of the data and the purpose of the analysis (e.g., description or prediction).

3. Critically examine the statistical significance of the result, making proper allowance for spatial coherence, autocorrelations and smoothing, and data selection.

4. Test the result on one or more independent data sets or subsets of the original data.

5. Endeavor to derive a physical hypothesis which can be tested on independent data, preferably at some other stage in the hypothesized chain of cause and effect.

6. Estimate the practical significance of the result, e.g., the fraction of the relevant total variance which can be predicted or explained.

7. Carefully explain the properties and limitations of the data, the statistical methods used (including data selection and smoothing), and any assumptions, reservations, or doubts.

8. Do not overstate the statistical or practical significance of the results.

Other objections to solar-climate research can be found in *Salby and Shea (1991)* and *Dewan and Shapiro (1991)*. Both of these papers attack the statistical aspects of the relationships outlined in *Labitzke and van Loon (1988)* linking solar activity and the QBO to north-pole temperatures. However, the unconvincing statistical relationships often found in solar-climate publications (*Pittock, 1983*) have, perhaps, created an environment of unnecessary scepticism. For instance, *Taylor (1986)* reviewed the links between the solar wind and winter tropospheric vorticity, and found that uncertainties within the field had "contributed inappropriate biases on both sides of the issue…" (page 329). Therefore, while it is necessary to acknowledge the shortcomings and limitations in the field of solar-climate relationships, it is important that each study be evaluated individually and not automatically discredited simply because it deals with a contentious topic.

2.3 Geomagnetic activity and the lower atmosphere

Despite the large number of studies examining the possibility that geomagnetic activity influences the lower atmosphere, there is no definable 'current understanding' in this field. There are, however, a number of recurrent themes and suggestions that appear in the modern literature. This section briefly traces the modern development of this field, while the following sections describe some of the more common notions, and inconsistencies, that are evident in the literature. Section 2.3.1 describes relationships between geomagnetic activity and the weather, which are discussed in many publications, while section 2.3.2 describes some of the (limited) literature that focuses on longer-term (annual/decadal) links between geomagnetic activity and climate.

One of the earliest published examples of the modern analysis of the geomagnetic forcing of the lower atmosphere is *Macdonald and Woodbridge's (1959)* paper. Their study examined changes in 'jet stream' level (300 hPa) circulation patterns following geomagnetic disturbances. Using the superposed epoch analysis method, they found that, for the 1956/57 and 1957/58 winters, troughs in atmospheric waves appearing in the Alaska-Aleutian area roughly three days after a geomagnetic disturbance tended to develop larger amplitudes. *Macdonald and Woodbridge (1959)* did not specify a physical mechanism that could account for the observed relationship, nor did they consider the larger climatic implications of their results. Nevertheless, their results stimulated a number of further studies, which use the same techniques and generally examine the same parameters.

Macdonald and Roberts (1960) also used the superposed epoch analysis method, albeit with slightly different key dates, to reanalyse the earlier results of *Macdonald and Woodbridge (1959)* and to extend them temporally with data from October 1958 to March 1959. Apart from confirming earlier results, *Macdonald and Roberts (1960)* were able to make the important conclusion that the time delay between a geomagnetic event and changes in atmospheric circulation is not constant, and subsequently the geographic nature of the relationship varies as each individual trough maximises at a different location. Further studies (*Woodbridge, 1971; Roberts and Olsen, 1973*) confirmed the earlier results with the use of additional data, but did not elaborate much on potential mechanisms.

Wilcox et al. (1973) also used the superposed epoch analysis method to examine the response of the 300 hPa northern hemisphere, winter atmospheric circulation to solar events. Interestingly, *Wilcox et al.* only examined the impact of one particular solar phenomenon – changes in the solar magnetic sector structure. Their results show a visually striking response in the vorticity area index (defined in *Roberts and Olsen, 1973*) beginning roughly one day before a solar magnetic sector crossing and ending roughly four days later (Figure 2.27). However, the validity of the results is questionable for a number of reasons. *Taylor (1986)* points out that subsequent work, including research by *Wilcox et al. (1983)*, shows that the relationship between solar magnetic sector boundary crossings and the vorticity area index is only evident between 1963 and 1973, and fails beyond 1973. Furthermore, *Burns et al. (1980)* found that the relationship is not evident in the southern hemisphere. It is also unclear why Wilcox *et* *al.* singled-out a particular type of solar event, solar magnetic sector crossings[29], from a wide range of solar phenomena.

Recent research has followed along these similar lines. Superposed epoch analysis remains the tool of choice for researchers studying geomagnetic activity influences on the weather. Most of the studies are still restricted to the northern hemisphere only and the vast majority of studies focus on daily relationships. One very encouraging sign is that most researchers have taken to examining possible mechanisms. Although the field is still contentious, there are many important concepts and developments in the recent literature, and these are presented separately in the following sections for weather and climate timescales.

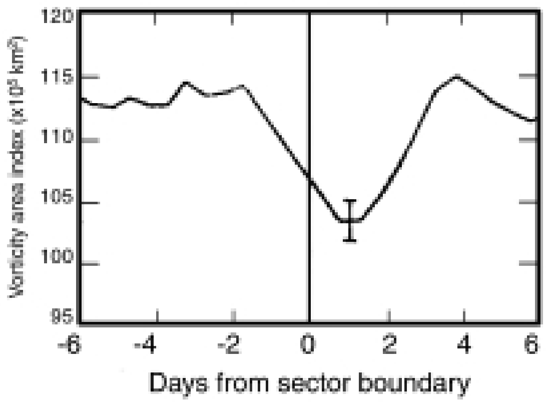

Figure 2.27. The response of the VAI index to solar magnetic sector crossings (from *Wilcox et al., 1973*). This figure shows a large drop in northern hemisphere vorticity, beginning one day before a solar sector magnetic boundary crossing, and lasting up to three days after the crossing. This relationship has motivated a large number of other, similar, solar-weather studies. However, it was found that the link between vorticity and boundary crossing is not evident in later years (see *Taylor, 1986*)

2.3.1 Geomagnetic activity and weather

One aspect of geomagnetic/weather relationships that shows a certain degree of coherence between studies is the timing of the effect. In the vast majority of studies, the lower atmosphere responds to a geomagnetic disturbance within seven days. Table 2.5 lists a number of studies that have used superposed epoch analysis to examine the

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[29] The solar magnetic field, also termed the interplanetary magnetic field (IMF), forms a spiral as it flows from the sun due to the 27-day solar rotation. Above the equatorial plane of the spiral the IMF is northward directed – below it, it is southward directed. The nature of the sun-earth geometry is such that the earth's position varies relative to the equatorial plane. See http://pluto.space.swri.edu/IMAGE /glossary/IMF.html for more information. When the earth is above the plane, it is exposed to the northward IMF, and conversely, when it is below the plane it is exposed to a southward IMF and geomagnetic disturbances are more likely.

relationship between geomagnetic activity and the weather, along with the atmospheric parameter studied and the timing of the response. The table demonstrates that the atmospheric response to geomagnetic activity is relatively rapid. However, it also shows that the average response time can sometimes be spread over a number of days. The superposed epoch analysis technique does not reveal if this spread is due to a long-lasting response with a fixed delay or a short-lived response with a slightly variable delay. *Vovk et al. (2000)* noted that the delay between Forbush decrease events and responses in Antarctic temperature, pressure, and wind, could be approximated by a quasi-exponential curve. Therefore, it is possible that the actual delay between geomagnetic activity and the associated atmospheric response(s) is a function of the magnitude of the geomagnetic event. This suggests that the atmospheric response is composed of short-lived events with variable delays.

The table also specifies whether a 'flare' effect was noted by the researchers. Many studies describe an atmospheric 'response' that precedes the geomagnetic events, usually by less than three days. This is generally associated with solar proton events or the solar ultraviolet enhancement that is associated with flares and is nearly always manifested in the atmosphere in the opposite way to geomagnetic activity.

The timing of the atmospheric response is particularly significant for possible mechanisms. In some cases, the atmospheric response occurs on the same day as the geomagnetic disturbance and associated Forbush decrease. Such a rapid response precludes mechanisms involving the coupling of the upper atmosphere to the lower atmosphere. In fact, it even disqualifies mechanisms that involve the propagation of stratospheric disturbances to the lower atmosphere[30]. However, with some exceptions (notably *Stening, 1994* and *Tinsley and Deen, 1991*), the studies in Table 2.5 generally

[30] The reported time required for stratospheric perturbations to propagate down to the surface varies considerably. For instance, *Baldwin and Dunkerton (2001)* indicate that stratosphere to troposphere propagation requires two to three weeks. Conversely, *Kodera et al. (1990)* report that strengthening of stratospheric westerlies in December have an impact on the troposphere during the following February. Despite the variation in the times, they all greatly exceed the very rapid (one to three days) atmospheric response to geomagnetic activity that most studies describe. At this point, it is not suggested that any of the above mentioned stratospheric disturbances have their origins in geomagnetic or solar activity – their suitability as solar-climate and solar-weather mechanisms is investigated in chapter five.

do not test for a possible atmospheric response outside of about ±10 days from the key date. It is possible that a significant atmospheric response occurs at larger lag intervals. The use of a limited time range in the superposed epoch analysis method limits the scope of the results and casts doubt on their validity. This will be demonstrated in chapter four, which examines the day-to-day response of the atmosphere to geomagnetic events.

There is a strong seasonal component to the relationship between geomagnetic activity and the weather; links between the two are generally thought to be a winter phenomenon. For most studies, the relationships are either strongest in winter (*Veretenenko and Pudovkin, 1995*), or evident only in winter (see *Wilcox et al, 1973*). The seasonal nature of solar-weather relationships is evident even in the earlier studies (*Macdonald and Woodbridge, 1959*), though the reason for this has not been satisfactorily explained. There are a few suggestions but by far most studies do not explain the seasonal nature of their results.

Danilov and Laštovička (2001) suggest that the reason that the tropospheric response to solar activity is more developed in winter is because the winter atmosphere is less stable. This view is shared by *Gabis and Troshichev (2000)*, who suggest that stratification in stratospheric zonal circulation is depressed in winter and greatest in summer. Winter is therefore the time when small external influences such as solar and geomagnetic activity are more likely to have an impact on stratospheric circulation.

Tinsley and Deen (1991) suggest that winter corresponds to a time of maximum cyclogenesis, hence the propensity for a winter vorticity response. Similarly, they note a stronger response over midlatitude ocean sections that correspond to regions of maximum cyclogenesis. This explanation is not suitable for the winter preference that *Veretenenko and Pudovkin (1995)* attach to cloudiness variations over land in response to Forbush decrease events. For their results, Veretenenko and Pudovkin attribute the winter preference in cloud cover reductions to the seasonal variation of cloud types. The effect, they conclude, is largest on high-level cirrus clouds. However, low-level clouds are twice as frequent during the summer months than they are in the winter months, and as the cloud-cover data are derived from ground-based observations, there is less probability of high-level cloud being observed during summer.

Beyond this, there is a want of explanations for the seasonal nature of the geomagnetic/weather relationship. Studies that examine the solar-weather relationship at the daily level, and in the southern hemisphere, are rare. However, *Burns et al. (1980)* and *Stening (1994)* studied the southern hemisphere, and both found that the results are best during the southern *summer*. This suggests that the northern hemisphere winter preference is, in fact, part of a global January-February preference. *Burns et al.* evaluated the vorticity response to solar sector boundary crossings, in the same manner as *Wilcox et al. (1973)* did for the northern hemisphere. They found that although the results are not statistically significant, the southern hemisphere vorticity shows a similar response to solar activity in the summer months as the northern hemisphere vorticity in winter[31]. *Stening (1994)* examined 25 years of Australian radiosonde data and found a statistically significant response, three days after the key date, in atmospheric temperature over Alice Springs. He reported that the effect is strongest in January-February. *Burns et al. (1980)* suggested that the global January-February effect might be a function of the earth's orbit, and that the January peak in global insolation might be an important factor. *Stening (1994)* attributed the global January-February effect to changes in the global electric field, which *Märcz (1990)* has shown to be most responsive to solar activity during these months. Indeed, it is not only the seasonal nature of the geomagnetic/weather link that is unclear, but also the mechanism by which geomagnetic activity influences the atmosphere, especially on the day-to-day timescale.

The modern literature, however, tends to be divided between two closely related mechanisms. The first is the Tinsley mechanism, involving the electrofreezing of cloud condensation nuclei (refer back to section 2.2.8). The second involves changes in atmospheric transparency, which *Pudovkin and Raspopov (1992)* relate to the influence of cosmic rays on the composition of the atmosphere, and which ultimately relates to

[31] *Burns et al. (1980)* also found an "almost significant" response in vorticity in the Australian sector. Interestingly, this occurred in the southern winter, and therefore further confounds the seasonal nature of geomagnetic/weather links.

changes in the radiative properties of the atmosphere as well as cloud cover variations. However, in recent papers (*Veretenenko and Pudovkin, 1997*; *Pudovkin and Morozova, 1998*), the atmospheric transparency mechanism is converging with the Tinsley mechanism, so that it is now generally suggested that daily solar/weather links occur through the cosmic ray modulation of cloud cover.

There is also some uncertainty regarding the spatial nature of geomagnetic-weather relationships. Three points about the spatial nature of the daily relationships can be gleaned from the current literature:

1. Solar and geomagnetic weather links seem to be different between the southern and northern hemisphere. Despite the paucity of studies examining the links in the southern hemisphere, it seems that geomagnetic/weather links are generally restricted to the northern hemisphere. It may be that the lack of high quality, temporally extensive data for the southern hemisphere has hindered the detection of a solar influence at the daily level.

2. Not only are these links limited to the northern hemisphere, but it has also been suggested that, at the daily level, the tropospheric signature of solar activity is "macroregional", and that the north Atlantic/European and the Siberian/Aleutian regions are the most 'sensitive' to solar forcing (*Danilov and Laštovička, 2001*).

3. The influence of geomagnetic activity on the weather is dependent on latitude. Numerous studies examining solar and geomagnetic forcing of weather in Russia report a latitudinal influence (see, for instance, *Veretenenko and Pudovkin, 1995*). *Veretenenko and Pudovkin (2000)* also report that the effect of cosmic rays on solar radiation input depends strongly on latitude. By using a number of stations covering a range of latitudes, they found that a negative correlation between solar radiation and cosmic ray events at high latitudes, and a positive one at lower latitudes.

In some of the recent literature, there is the suggestion that the daily link between solar activity and climate is modulated by a number of factors, including the QBO and volcanic aerosols. *Labitzke and van Loon (1988)* revealed that the relationship between the solar cycle and northern stratospheric polar temperatures is modulated by the QBO. The means by which the QBO influences the solar effect on the stratosphere, at the annual level, is not clear[32]. It is therefore surprising that many researchers have incorporated the QBO into daily solar-weather links. In general, researchers have found that geomagnetic-weather links are stronger during particular QBO phases (*Tinsley et al., 1989*; *Besprozvannaya et al., 1997*). Although the role of the QBO within daily solar-weather links is, like their annual counterparts, also unclear *Tinsley and Deen (1991)* suggest it could be related to its role in the dynamic coupling of the stratosphere to the troposphere and the resultant chemical transport. Nevertheless, given that its role is uncertain at both the annual and daily levels, its inclusion in geomagnetic-weather studies requires more thought.

It has also been suggested, for example, by *Kirkland et al. (1996)* and *Besprozvannaya et al. (1997)*, that geomagnetic/weather links are modulated by the presence of volcanic aerosols in the atmosphere. This is particularly the case for the relationship described in *Wilcox et al. (1973)*, which *Kirkland et al. (1996)* suggest is restricted to periods following volcanic eruptions because of the role that a high stratospheric aerosol loading plays in the Tinsley mechanism. However, very few geomagnetic/weather studies incorporate stratospheric aerosol loading into their analyses, yet still manage to produce suggestive results. The role of both the QBO and volcanic stratospheric aerosols in the link between geomagnetic (and solar) activity and the day-to-day atmosphere is not clear. Chapter five suggests, however, that the stratospheric aerosol layer may play a crucial role in the geomagnetic activity forcing of the atmosphere at annual timescales.

Another contentious aspect of the study of day-to-day solar-atmosphere interactions is the use of superposed epoch analyses. The use of this method is universal in the field of

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[32] *Salby and Callaghan (2000)* present one possible explanation for the QBO modulation of solar-climate links in the stratosphere. They suggest that the QBO itself is influenced by the solar cycle. They find that during solar maxima, the equatorial wind in a winter season is both westerly and easterly, whereas outside of solar maxima the equatorial wind is either westerly or easterly.

solar-weather studies. The spatial and temporal variability of the diurnal atmospheric response to solar activity precludes the use of techniques such as correlations. The superposed epoch analysis method has numerous shortcomings, however, which will be examined in chapter four. Furthermore, many studies neglect to examine the statistical significance of the results. Chapter four will highlight a particularly dubious practice regarding the statistical significance of superposed epoch analysis results.

2.3.2 Geomagnetic activity and climate

Studies that focus on the long-term relationship between geomagnetic activity and the atmosphere, for example at the annual level, are relatively scarce. This section examines two in particular that are relevant to chapters three and five of this study. The first is a link between geomagnetic activity and the North Atlantic Oscillation index, described in *Bucha and Bucha (1998)*. The second is a link between the geomagnetic AA index and decadal averages of global temperatures, outlined in *Cliver et al. (1998)*.

Potentially one of the most significant sun-weather relationships observed to-date, in both a statistical and practical sense, is the high correlation between the North Atlantic Oscillation and the geomagnetic AA index discovered by *Bucha and Bucha (1998)*. Unfortunately, this discovery has gone unnoticed in the climate literature, which largely still considers the North Atlantic Oscillation as 'enigmatic' *(Perry, 2000)* and possibly "the result of the aggregation of many stochastic weather processes" *(Stephenson et al., 2000)*. The results of *Bucha and Bucha (1998)* have only just now been updated by the research of *Thejll et al. (submitted 2002)*, who also compared the AA index to the North Atlantic Oscillation and found them to be linked at timescales of 7-10 years. Their results will be reviewed in chapter three.

Bucha and Bucha (1998) defined a zonal index of the North Atlantic Oscillation by differencing the zonal averages of sea level pressure between 35° and 65°N for November through to March. They subsequently found that for the period of 1970-1994, this zonal index was highly correlated (r = 0.68) to the geomagnetic AA index. They also found that the winter North Atlantic Oscillation index is correlated (r = 0.56) to the AA index for the period 1970-1991. Another important observation in *Bucha and Bucha*

(1998) is that the correlation values are substantially less when the sunspot number is used instead of the AA index. For example, the correlation between the winter North Atlantic Oscillation Index and the sunspot number for 1970-1991 is only 0.15.

They also found an inverse relationship between geomagnetic activity and the North Atlantic Oscillation zonal and winter indices for the period 1900-1944. The correlation coefficient for the zonal index (described above) and geomagnetic activity is -0.44, while for the winter index it is -0.31. Correlation values that change sign and/or magnitude with time are often seen as an indication that the correlations are, in fact, not real (see, for instance, *Pittock, 1983*). However, for the case of the North Atlantic Oscillation and the AA index, *Bucha and Bucha (1998)* presented an explanation as to why the correlations have changed sign after ~1940, which is described here briefly. During low geomagnetic activity, high-pressure cells occur over the polar region and Greenland, and a low-pressure cell occurs over Europe; a weak zonal flow results. With "slightly below-normal" (*Bucha and Bucha, 1998*) geomagnetic activity the high-pressure cell found over Greenland during periods of low activity moves south-eastward and joins the Azores High to form an intense high-pressure ridge. The high-pressure ridge blocks warm air from the Atlantic from flowing onto Europe, which is instead subject to Arctic air from the north or the east. At this stage the North Atlantic Oscillation zonal index is negative, and is less than the zonal index for even lower geomagnetic activity. Conversely, high geomagnetic activity sees the intense high-pressure cell relocated south-east over Europe and the intensification of the Icelandic low. In this instance, the zonal North Atlantic Oscillation index is positive. *Bucha and Bucha (1998)* suggest that this explains the reversal of the correlations for the periods 1900-1944 and 1970-1994. During the earlier period, geomagnetic activity was low (high zonal index) or below-normal (lower zonal index) and the correlations were therefore negative. During the later part of the century, geomagnetic activity was typically high (highest zonal index) or below-normal (lower zonal index), and the relationship between the two was therefore positive. This explanation for the reversal of the correlations is evaluated in chapter three.

Despite the observations that *Bucha and Bucha (1998)* presented relating the North Atlantic Oscillation to geomagnetic activity, and their subsequent explanation for the reversal of these correlations after 1945, very little progress, if any, has been made on this particular relationship. The most important aspect of this relationship is that it could afford a method of predicting the North Atlantic Oscillation well in advance. To do this, however, requires a detailed understating of this relationship, especially the reversal of the correlations. It also has implications for recent changes in the North Atlantic Oscillation and the Arctic Oscillation as well as global warming. The relationship between geomagnetic activity and atmospheric circulation is evaluated in chapter three, which also tests for a similar relationship in the southern hemisphere equivalent of the Arctic Oscillation, the Antarctic Oscillation.

Another solar-climate relationship that is potentially significant to recent climate change is the similarity between geomagnetic activity and global surface temperatures (*Cliver et al, 1998*). *Cliver et al.* found high correlations (r = 0.90, and r = 0.95) between decadal means of geomagnetic activity and global surface temperature and geomagnetic activity minima values and global surface temperature, respectively (Figure 2.28). Their results prompted them to suggest the there is a "long-term component of solar irradiance that underlies the 11-year cyclic component" (*Cliver et al., 1998*; page 1035), which has a significant impact on global surface temperature. They do concede, however, that the solar influence on global temperature may not be the result of solar irradiance changes, but that it could be a function of the solar wind.

Many aspects of this relationship warrant further investigation. The spatial and seasonal pattern of the relationship is of particular interest, as it will allow the deduction of possible solar-climate mechanisms. The results in *Cliver et al. (1998)* are for global surface temperature, and the statistical shortcomings associated with their results have been described previously in this chapter. It is important to understand the regional nature of this relationship, especially in the southern hemisphere. These considerations are, however, secondary to the main aim of this thesis, which is to examine the potential role of geomagnetic activity in recent climate change via atmospheric circulation. Analyses comparing long-term changes in geomagnetic activity to regional surface temperatures are therefore presented in the following paragraphs. They represent an important aspect of solar-climate relationships that warrant further investigation but that are a separate concern to the geomagnetic forcing of the annular modes described throughout the rest of this thesis.

Monthly mean temperature records were used to examine the spatial and seasonal pattern of long-term links between geomagnetic activity and surface temperature. The monthly mean temperature data are from the *GHCN* v2 data set[33]. Only a small subset of the available data were used. To be included in the analyses, each climatological station had to provide uninterrupted coverage from 1900 to 1990. Using a uniform record length in the correlation process avoids the bias that record length introduced to the magnitude of the correlations. The selected data were smoothed using an 11-point moving average, in the same manner as the global and hemispheric data analysed in section 2.2.11, and correlated to the smoothed AA index. The correlations therefore extend from 1905 to 1985, as five years were lost from the end of each record with the use of the 11-point moving average filter.

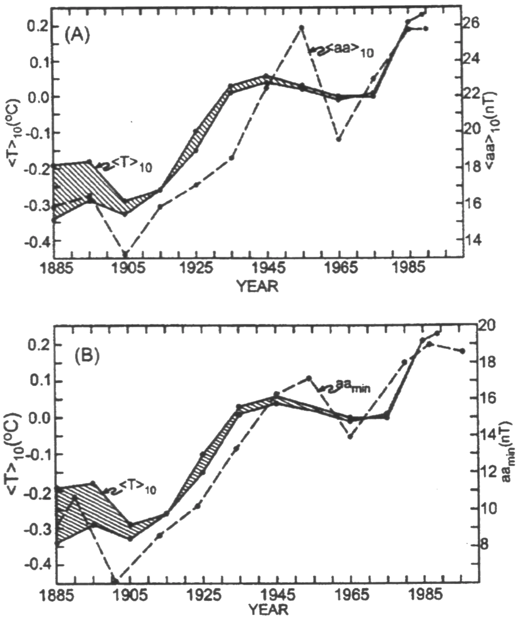

Figure 2.28. Decadal averages of (a) geomagnetic activity and global temperature, and (b) geomagnetic activity minima values and global temperature (from *Cliver et al., 1998*). Both graphs show a striking similarity between long-term geomagnetic activity and global surface temperatures, from 1885 onwards. Decadal averages of geomagnetic activity are shown by a stippled line, and temperature data are presented in the shaded envelope.

Correlation coefficients for 419 unique records, from the original 1,976 correlations, are displayed in Figure 2.29. The distribution of the records is limited because there are

[33] Described in *Peterson and Vose, (1997)*. Global historical climatology network, available from the *NOAA* page, http://www1.ncdc.noaa.gov/pub/data/ghcn/v2/

very few records outside of North America, Europe, and Japan. As monthly data were used, there were sometimes up to twelve records for each location, one for each month. While it was found that averages of hemispheric temperature data show no seasonal variations in their correlations to the AA index (Appendix A), geomagnetic activity correlations with the regional data varied greatly by month. In some cases, the amount of variability between correlations for different months was very large, such that the greatest positive correlation was matched by a negative correlation of similar magnitude in other months.

Only the highest correlation for each station is shown in Figure 2.29, and the month in which the highest correlation occurred has been noted. Because of this strong variability in the monthly correlation coefficients, which generally have no particular seasonal pattern, it can be concluded that the geomagnetic activity signal in global temperatures is not evident in regional temperature data. It is evident, in Figure 2.29, that with the exception of the southeast area, the correlations in the North American region are generally positive and of moderate magnitude. What is not evident from the figure, however, is that there is no consistency in the seasonality of the results. This does not provide strong support for a geomagnetic activity influence on land temperatures at regional scales. The same inconsistency is generally evident in all other regions.

There is one interesting exception, however. Correlation results for Japan are consistently of the same sign and magnitude, and furthermore, have a very strong seasonal pattern. Figure 2.30 shows the frequency histogram of the months with the highest correlations for the Japan records. A clear preference for November is evident – maximum correlations occur in this month over 50% of the time. The correlations are also of very high magnitude, ranging[34] from 0.56 to 0.95 and averaging 0.82. Even once the impact of serial correlation of the effective number of observations is considered many of the correlations for the Japanese stations are statistically significant at the 95% confidence level. Figure 2.31 shows the results for the Japanese stations. Unfortunately,

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[34] With the exclusion of the results for Shanghai, China, which although in a similar region (bounded by 120°E-146°E and 22°N-46°N), show a negative relationship (r = -0.63).

the Japanese data provide the only suitable records in the region, so the extent of this spatial and seasonal pattern is difficult to determine. A similar, but much reduced, seasonal preference is evident in the entire data set, but the magnitude of the correlations elsewhere is negligible and inconsistent.

The results indicate that while geomagnetic activity is only evident as a subtle signal in global or hemispherically averaged temperature records, it is also possible to observe it at the regional level for a small portion of the available data. The findings of *Sakurai (2002)* may be pertinent to these results. Sakurai found an 11-year solar cycle periodicity in records of 'sky brightness' over Japan. The solar cycle signal in sky brightness operates at a different timescale to the temperature correlations described here (annual and decadal versus long-term/interdecadal). Nevertheless, some aspects of *Sakurai's (2002)* observations are relevant to these temperature results. Firstly, Sakurai observes that the brightness changes are not the result of changes in the solar corona and suggests that they occur through the solar-activity modulation of atmospheric aerosols. Secondly, Sakurai notes a lag of two to four years between the peaks in the sunspot number and sky brightness, with sunspot maxima leading brightness maxima. Analyses performed in section 2.2.4 have shown that geomagnetic maxima typically lag behind sunspot maxima by between -2 and +5 years lag, and that in cases when geomagnetic maxima precede sunspot maxima there is a second geomagnetic maximum four years later. This means there is typically a peak in geomagnetic activity between two and five years after sunspot maxima – a timeframe that suits Sakurai's results. Geomagnetic activity can possibly influence atmospheric aerosols or clouds through its impact on cosmic rays. The link between cosmic rays and aerosols has been suggested by many researchers (*Dickinson, 1975; Roldugin and Vashenyuk, 1994; Yu, 2002*), so it is possible that the changes in sky brightness observed in *Sakurai (2002)* are the result of geomagnetic activity and that this relationship forms part of the mechanism responsible for the regional correlations to monthly mean temperature.

Mendoza et al. (2001) also found an indication of geomagnetic activity in central Mexican minimum extreme temperature data. They used monthly and annual data, spanning ~1920 to ~1990, from five Mexican stations and reported a correlation coefficient of 0.65 between 10-year averages of station-averaged data and the AA index.

It may prove fruitful, therefore, for future studies to consider the regional nature of geomagnetic/temperature correlations. However, as *Mendoza et al. (2001)* indicated, longer time series are required before the results can achieve statistical significance. This is largely because of the amount of smoothing used within such studies and it will therefore be a number of decades before such a study can yield conclusive results.

2.4 Overview and Discussion

This chapter has presented an overview of solar-climate relationships. Section 2.2 reviewed the field of solar-climate research in general, while section 2.3 focussed on relationships between geomagnetic activity and climate. A number of conclusions and observations can be drawn based on the overview presented here:

1. The field of solar-climate relationships is unique in that it was born out of assumptions, and to some degree, is still perpetuated by assumptions. This is in direct contrast to most other scientific research, and fails to conform to the generally held perception that scientific hypotheses and research exist to address specific problems, and are not simply the result of rampant speculation. Beginning with *Herschel's (1801)* bold assumption, that climate should vary under the influence of sunspots, countless other solar-climate relationships have been described in the past 200 years describing links that do not address any specific climatic problems. Instead, they seek to validate the assumption that changes in the sun must, somehow, be manifested as changes in our climate[35] and perpetuate a field that has not, to date, justified it's own existence.

This is no more evident than in research linking geomagnetic activity and climate/weather. Early research, like that of *Stagg (1931)*, had little cause to assume a link between the two (other than local variations in the geomagnetic field caused by

[35] It is possible to cite some instances where researchers have encountered the solar signal in climate data without explicitly searching for it. For example, *Douglass (1909)* found an 11.3-year periodicity in tree-ring widths, while *Barnett (1989)* encountered an 11-year solar cycle in global sea surface temperature while examining quasi-biennial variations.

meteorological variations). In fact, it is a matter of some curiosity as to why it was even assumed that geomagnetic activity could be a source of meteorological events!

Many contemporary studies (including, in part, this thesis) are motivated by the need to expand upon or evaluate previous studies, which themselves are based on the assumptions that solar variability must influence climate. As such, some modern studies are very much like their early predecessors in that they do not attempt to address any particular climatic enigma, but study solar-climate relationships simply for their own sake. This has hindered the general acceptance of the field of solar-climate relationships by the general climatic community and perhaps validated *Pittock's (1978, 1979)* suspicions that solar-climate relationships are of limited use. Of course, it could be argued that the climatic system is so complex and dynamic that anything that offers a potential insight into the workings of the atmosphere is a worthwhile pursuit.

2. Very few studies consider the greater implications of their findings and relate their results back to other, non solar-climate work. This is perhaps one of the more subtle factors that obviate the general acceptance of the field of solar-climate relationships, as well as the specific findings within the field. Many modern studies examining the relationship between long-term solar activity and terrestrial temperatures declare that their motivation is the need to clarify the solar influence on global temperatures, so that potential anthropogenic impacts can be better understood (see, for example, *Bucha, 1991*). In fact, some authors have evaluated the relative contribution of solar and anthropogenic forcing on recent temperature changes (see, for example, *Lean et al., 1995*). However, this is an isolated example, and in general, there is very little interfacing between traditional climate studies and solar-climate studies. The climatic implications of what is, perhaps, the most compelling solar-climate relationship to-date – that of Labitzke and van Loon involving the stratosphere – have yet to be described in the solar-climate literature.

3. Surprisingly, there also seems to be reluctance, on the part of many solar-climate researchers, to relate their results to other findings within the field. This is unfortunate, because despite the large number of publications in this field there has been limited progress made in the 200-year history of this field of research. This leads onto another point regarding the validity of many of the results in this field.

The review presented in this chapter (as well as other literature not discussed here) suggests that solar-climate relationships are, supposedly, ubiquitous. The literature describes relationships at all timescales, from hourly changes *(Stagg, 1931)* to long-term changes (see, for instance, *Eddy, 1976, 1977*; *van Geel et al., 1999*). Solar-climate links have been proposed for practically every climatic and meteorological parameter that has ever been measured. These include air *(Thejll and Lassen, 2000)* and sea *(Barnett, 1989)* temperatures, sea level *(Woodworth, 1985)*, vorticity *(Burns et al., 1980)*, rainfall *(Currie and Vines, 1996)*, geopotential heights *(Labitzke, 2001)*, clouds *(Svensmark and Friis-Christensen, 1997)*, ozone *(Varotsos, 1989)*, river flow (*Sytinskiy and Postnikov, 1995*), planktonic foraminifera (*Castagnoli et al., 1999*) and so on.

Similarly, at one time or another, every aspect of solar activity has been related to climate, including the commonly used sunspot number, geomagnetic activity, solar-sector boundary crossings (*Wilcox et al., 1973, Burns et al, 1980*), solar proton events (*Pudovkin and Morozova, 1997*), and variations at longer timescales, such as the 206-year period (*Hodell et al., 2001*). If even half of the suggested relationships were valid then solar activity would be the dominant driver of earthly climate and weather and the reality of a solar influence on climate would be undoubted. It is obvious, therefore, that there is a desperate need to evaluate the many solar-climate relationships that abound in the literature and, if possible, to reconcile them into one hypothesis that incorporates all the different solar sources, climatic impacts, and physical mechanisms.

4. It is obvious that the lack of proven physical mechanisms present a considerable problem to solar-climate researchers. Although there is an amazing abundance of hypotheses regarding the method by which solar activity may influence the lower atmosphere (see chapter five), very few have been tested. Indeed, it is common for researchers to simply report their observations and then leave the consideration of the suitable mechanism up to the reader. This is usually done by summarising the current hypotheses regarding possible solar-climate mechanisms into a diagram (see, for example, *Bochníček et al., 1999; van Geel et al., 1999*) or listing them in the text *(Cliver et al., 1998)*.

5. The southern hemisphere is grossly understudied in the field of solar-climate relationships. The examination of solar-climate relationships in the southern hemisphere is important, not only because it is relatively neglected in the literature, but also because it can provide insights into solar-climate relationships in the northern hemisphere. The availability of the *NCEP/NCAR* reanalysis data addresses the limitations associated with data availability in the southern hemisphere and is incorporated in this thesis to examine geomagnetic activity variations in both hemispheres.

In light of these points, one way to narrow down the possible mechanisms (as well as evaluating the climatic significance of the results) is to examine the spatial, temporal, and seasonal aspects of the solar-climate relationship in question. It is also useful to examine the solar-climate relationship on different timescales (such as decadal and interannual, as well as daily) and compare the results when different indices of solar activity are used. This is demonstrated in this thesis, which examines what is currently the most promising aspect of solar-climate relationships – the geomagnetic forcing of atmospheric circulation.

3 Geomagnetic activity and atmospheric circulation

3.1 Introduction

Changes in atmospheric circulation, as represented by the Arctic, North Atlantic, and Antarctic Oscillations, impact upon global climate. Despite the important role these oscillations play in recent climate change (*Hurrell, 1996; Gong and Wang, 1999; Thompson et al., 2000*) their forcing mechanisms and behaviour are not well understood (*Perry, 2000*). For example, it is not clear to what extent changes in the North Atlantic Oscillation are an accumulation of stochastic weather events (*Stephenson et al., 2000*), the product of ocean-atmosphere coupling (*Marshall et al., 2001*), or the result of internal atmospheric dynamics, possibly originating in the stratosphere (*Perlwitz and Graf, 1995*). There are also a number of specific uncertainties about these atmospheric modes. Many authors note a period of uncharacteristically low values in the North Atlantic Oscillation and Arctic Oscillation indices between the 1950s and 1970s (*Greatbatch, 2000*), followed by a strong positive trend extending to the present day (*Stephenson et al., 2000*). Although *Wunsch (1999)* has described similar non-stationary periods in a synthetic North Atlantic Oscillation index, one cannot exclude the possibility that the recent changes in these indices of atmospheric circulation are deterministic. The literature also expresses uncertainty about the origin of decadal variations evident since the 1960s (*Hurrell, 1995*), the year-to-year winter persistence of anomalies (*Stephenson et al., 2000*), and the nature of interannual variations of both the Arctic Oscillation and North Atlantic Oscillation (*Feldstein, 2000*). These features are also evident, to some degree, in the dominant mode of variability in the southern hemisphere, the Antarctic Oscillation (*Thompson et al., 2000*).

There are a number of reasons to suspect that the aforementioned uncertainties can be explained in part by solar activity, as represented by geomagnetic activity. For example, geomagnetic activity also exhibits an uncharacteristic period of low values centred in the 1960s, and its power spectrum is dominated by decadal variations (refer to Figure

2.13). The most compelling evidence that the recent changes in these atmospheric indices are related to solar-modulated geomagnetic activity is found in *Bucha and Bucha (1998)*, who presented correlations linking the North Atlantic Oscillation to geomagnetic activity (already described in section 2.3.2). *Bucha and Bucha (1998)*, however, did not relate their findings to the currently unexplained aspects of the North Atlantic Oscillation. Furthermore, many questions remain unanswered. Foremost is the question of whether any relationship between solar activity and atmospheric circulation is evident in the southern hemisphere. Other questions relate to the nature of this relationship at different timescales, especially the interannual level, as well as its temporal and seasonal characteristics.

This chapter therefore tests the hypothesis that solar-modulated geomagnetic activity is a significant forcing mechanism behind recent changes in global atmospheric circulation. It begins by providing an overview of the Antarctic, Arctic, and North Atlantic Oscillations, and then describes the data and methods used. The results are discussed with reference to existing solar-climate and general climate theories, especially the change in the northern hemisphere climate regime in the 1960s (*Knox et al., 1988; Tourre et al., 1999; Venegas and Mysak, 2000; Cavalieri and Häkkinen, 2001*), and scrutinised according to *Pittock's (1978, 1979)* criteria for establishing solar-climate relationships described in the previous chapter.

3.2 The Annular Modes

3.2.1 Antarctic Oscillation

Gong and Wang (1999) describe the Antarctic Oscillation as the 'alternation of atmospheric mass' between the southern middle and high latitudes (Figure 3.1). They define the Antarctic Oscillation index as the difference between the normalised zonal-mean sea level pressure at 40° and 65° south. *Thompson et al. (2000)* note that the Antarctic Oscillation has drifted towards higher values in the past decades, after a period of low activity in the 1960s and 1970s. They also note that although the Antarctic Oscillation is evident in the troposphere for all months, tropospheric circulation is coupled to the stratosphere only in November. The relevance of the oscillation to recent climate change is not as comprehensively documented as that of the Arctic Oscillation, though *Gong and Wang (1999)* assert that it has "potential for clarifying climate regimes in the southern hemisphere, similar to how the [North Atlantic Oscillation] and the [North Pacific Oscillation] has been used in the northern hemisphere" (page 461).

In the most recent studies (for example, *Wallace and Thompson, 2002*) of the Antarctic and Arctic Oscillations, these phenomena are referred to as the 'Southern Atmospheric Mode' (SAM) and the 'Northern Atmospheric Mode' (NAM) respectively. These abbreviations are adopted in the present study to avoid potential confusion arising from the use of abbreviations such as 'AAO' and 'AO' for atmospheric indices and 'AA' for geomagnetic activity.

3.2.2 Arctic Oscillation

Thompson and Wallace (1998) defined the Arctic Oscillation (hereafter abbreviated to the NAM) as the 'leading empirical orthogonal function of the wintertime sea-level pressure' in the northern hemisphere. It is evident at all levels of the lower atmosphere (Figure 3.2). At the surface, it resembles the North Atlantic Oscillation (*Baldwin and Dunkerton, 1999*).

Many researchers have described the NAM and the North Atlantic Oscillation (hereafter NAO) as different manifestations of the same phenomenon[36] (*Baldwin and Dunkerton, 1999; Kerr, 1999*), so it can be seen that the NAO and NAM are, to some extent, interchangeable. There are a number of important differences, however, and for an overview of these refer to *Wallace (2000)*. The principal difference is the method by which they are derived. While the NAM is typically represented by the leading empirical orthogonal function in the analysis of northern hemisphere climate parameters, such as sea level pressure, the NAO can be derived from a normalised index

[36] In comparing the Arctic Oscillation and North Atlantic Oscillation, *Ambaum et al. (2001)* concluded that the North Atlantic Oscillation is "…more physically relevant and robust for N. Hemisphere variability than the [Arctic Oscillation] paradigm…" but conceded that the North Atlantic Oscillation might still be explained by the physical mechanisms associated with the Arctic Oscillation.

based on sea level pressure for stations representative of the Icelandic low and Azores high, such as Stykkisholmur, in Iceland, and Lisbon, in Portugal, respectively (*Hurrell, 1995*).

Baldwin (2000) suggests that the time averaging of the station data used in the derivation of the NAO index implies that short-period fluctuations are not well represented. Moreover, despite their similarity, there are other benefits for the use of the NAM over the NAO. *Thompson et al. (2000)* prefer the NAM because it has a southern hemisphere equivalent, its intraseasonal variability is more pronounced, and it has greater significance to recent climate trends.

Like the SAM, the NAM can be described as the oscillation of atmospheric mass between polar and mid-latitude regions (*Thompson et al, 2000*), as shown in Figure 3.2. At sea level, positive values of the NAM index are associated with stronger than normal westerlies at 55° N and lower than normal sea level pressure at the pole (*Thompson et al, 2002*).

The NAM and NAO play an important role in the climate dynamics of the northern hemisphere. The NAO accounts for over 30% of sea level pressure variations in the northern hemisphere (*Hurrell, 1996*). In the North Atlantic region, differences in sea level pressure exceeding 15 hPa are associated with changes in the NAO index of ±1.0 (*Hurrell, 1995*). The NAO has also been linked to atmospheric blocking in the North Atlantic sector (*Shabbar et al., 2001*), sea level changes within the Mediterranean (*Tsimplis and Josey, 2001*), Arctic sea ice export during winter (*Hilmer and Jung, 2000*), wind speed variability in the tropical North Atlantic (*George and Saunders, 2001*), and ozone concentrations in the stratosphere (*Appenzeller et al., 2000*). The Arctic Oscillation itself has also been linked to recent climate change. *Thompson et al. (2000)* indicate that between January and March, roughly 50% of the warming of the Eurasian continent, and 30% of warming across the northern hemisphere can be correlated directly to the Arctic Oscillation. It is evident, therefore, that variations in the NAM and NAO are climatically important, and it follows that any forcing of these oscillations by solar activity is likely to have practical significance for explaining recent climate change.

The Arctic Oscillation is associated with the strength of the stratospheric polar vortex (*Thompson and Wallace, 1998; Baldwin and Dunkerton, 2001*). One feature of the Arctic Oscillation that may have tremendous importance to solar-climate studies is that it is known to propagate from the stratosphere to the troposphere. *Baldwin and Dunkerton (1999)* have demonstrated that stratospheric polar vortex anomalies generally propagate downward to the troposphere over periods of roughly three weeks during winter. This period, January through March, when the northern stratosphere and troposphere are coupled and Arctic Oscillation-related variance is greatest, is termed the 'active season' by *Thompson et al. (2000)*. Although the exact mechanism behind this stratosphere-troposphere propagation is not known with certainty, they suggest that it is likely to involve the influence of stratospheric anomalies on planetary waves. Further examination of this phenomenon suggests that, on intra-seasonal timescales, the downward propagation from the stratosphere is a feedback response to upward propagating planetary waves that impact on stratospheric circulation (*Black, 2002*). However, on longer timescales *Black (2002)* suggests that the downward propagation of stratospheric variations is a direct forcing mechanism related to radiative processes.

The coupling between the troposphere and stratosphere, and the downward propagation of stratospheric changes to the troposphere, have been touted as a possible solar-climate mechanism in many studies (*Balachandran et al, 1999; Black, 2002*). Proof of a link between solar activity and the Arctic (as well as the Antarctic) Oscillations is essential to the validity of such a mechanism. However, except for the results of *Bucha and Bucha (1998)*, there is currently no published evidence of such a link using modern data and certainly none using indices of the Arctic and Antarctic Oscillations. The following sections therefore evaluate the influence of solar activity on these indices. The results can potentially provide support for, or disprove, a feasible solar-climate mechanism involving the coupling of the stratosphere and troposphere and may also prove useful in explaining recent changes in atmospheric circulation.

3.2.3 Data

Monthly indices of the Arctic and Antarctic oscillations were obtained from the *Annular Modes website*[37]. The monthly NAM index spans 1899 to 2000 (a total of 1,224 observations), and the SAM index spans 1958 to 1999 (504 observations). Both indices are the same as those used in *Thompson and Wallace (2000)* and *Thompson et al. (2000)*, and were derived, by their providers, from the regression of monthly anomaly fields on the leading principal component of data for each hemisphere. The NAM was derived using sea level pressure data and the SAM was based on 850 hPa geopotential height data to overcome the influence of Antarctic terrain (*Thompson and Wallace, 2000*). Figure 3.3 shows the winter NAM and the annual SAM indices. Note the trend towards higher values in the most recent decades, preceded by a period of low values in the 1960s as described in *Thompson et al. (2000)*.

Monthly and three-monthly values of the NAO index were obtained from the *University Corporation for Atmospheric Research* (UCAR) web page[38] for the period 1865 to 2000. The monthly NAO indices are derived using normalised sea-level pressure values between Ponta Delgada and Stykkisholmur/Reykjavik *(Hurrell and van Loon, 1997)*. Solar data were obtained from sources described in chapter two, and comprise monthly values of the geomagnetic AA index and the sunspot number.

3.3 Methods

This chapter examines a number of features of the possible relationship between solar activity and atmospheric circulation, largely through correlation coefficients. These include the behaviour of this relationship at various timescales, and temporal, seasonal, and spatial aspects of the relationship. Particular attention is also given to the statistical significance of the results. Each of these aspects of the analysis is described here.

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[37] http://www.atmos.colostate.edu/ao/Data/ao_index.html. The online data, and a description of their derivation, are provided by David Thompson.

[38] NOA index data provided by the Climate Analysis Section, NCAR, Boulder, USA, *Hurrell (1995)* http://www.cgd.ucar.edu/~jhurrell/nao.html

3.3.1 Timescales

The relationship between solar activity and atmospheric circulation was evaluated for the original unmodified data (hereafter the raw data) and for subsets of the original data at two timescales – decadal and interannual. Features of both the atmospheric and solar data support the separate study of decadal and interannual variations. Numerous researchers have indicated that the atmospheric circulation indices contain significant, unexplained decadal variations. For the SAM, *Gong and Wang (1999)* note a period of low values between 1960 and 1970, followed by higher values in the 1980s, and suggest that the decadal variations in the SAM warrant further research. Similarly, unexplained decadal variations are present in the NAO and NAM in recent times (*Hurrell, 1995; Stephenson et al., 2000*). These decadal variations are supplemented by short-term variations, in the range of two to five years, of unknown origin[39] (*Stephenson et al., 2000*). Furthermore, the geomagnetic AA index contains significant short-term variability as well as the dominant 11-year periodicity associated with the solar cycle. As Figure 2.13 demonstrated, variability in the sunspot number is limited to the decadal timescale. Because the vast majority of solar-climate studies use the sunspot number as an index of solar variability they are limited to the study of long-term (decadal) relationships. The use of the geomagnetic AA index allows the study of the much-neglected interannual solar-climate links.

Figure 3.4 demonstrates the procedure used to isolate the decadal and interannual variations from the raw data. The raw (unmodified) data for sample data, the January NAM and AA indices, is shown in 3.4a. Decadal variations were extracted from the raw data by applying a five-point unweighted moving average (*i.e.*, with a half-width of two years) to each index – the resultant time series are shown in Figure 3.4b. A moving average of order five was chosen based on the statement of *Stephenson et al. (2000)*, that there are "…substantial contributions from short-term 2-5 year variations" (page 1)

[39] *Feldstein (2000)* evaluated whether interannual variations in the NAO index can be considered as 'climate noise' by comparing it to a Markov process, and concluded that "… it is difficult to make a strong statement about the role of climatic noise and external forcing for the NAO" (page 4437). Interannual variations in the NAO data from 1958-1997 are dominated by external forcing, but the results are confounded by the presence of the long-term trend in the NAO index.

to the overall variance of the North Atlantic Oscillation. Spectral analysis of the resulting AA index time series (see inset in Figure 3.4b) reveals that the smoothing process has successfully removed the short-term variations. Figure 3.4c shows the short-term (interannual) variations for the same indices, which were derived by subtracting the decadal indices from the raw data. The spectral graph in 3.4c confirms that this process has removed the long-term variations in the AA index. The spectral properties of the NAM indices in Figure 3.4 are similarly modified by this process.

3.3.2 Temporal

The results of *Bucha and Bucha (1998)* have already indicated that the relationship between the geomagnetic AA index and the NAO index is not constant over time. Therefore, two techniques have been employed here to examine objectively the temporal nature of the relationship between solar and atmospheric indices – sliding correlations and the cumulative sum of the squares of deviations[40]. The sliding correlations are most suited to the decadal data, which is serially correlated due to the smoothing process, while the cumulative sum method was applied to the interannual variations.

The method of sliding correlations (also termed running correlations) is used in *Jacobeit et al. (2000)* to examine the relationship between zonal indices and European temperatures, and in *Chang et al. (2001)* to examine the relationship between the Indian summer monsoon rainfall and summer Niño-3 sea surface temperatures. In this study, 11-point correlation windows were used, with one-year increments. An interval of 11 years was chosen so that at least one complete decadal cycle was covered. Figures showing the results of the sliding correlation procedure are presented in the following results sections. The sole purpose of the sliding correlations is to highlight periods when the solar and atmospheric data are consistently related, not to demonstrate a statistically significant relationship.

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[40] Not to be confused with the cumulative sum of squares method used to detect change points in time series, as described in *Inclán and Tao (1994)*.

Taylor et al. (2002) use cumulative sums to demonstrate that weak climatic signals can be extracted from ecological data, specifically the response of zooplankton to the position of the Gulf Stream. This technique involves calculating the sum of the squares of the difference between two normalised time series, and *Taylor et al. (2002)* suggest that it is “a sensitive test of whether the relationship is constant with time” (page 629). It is therefore ideal for the detection of solar-climate relationships, which may be temporally inconsistent as well as weak. The slope of the cumulative sums indicates the amount of correlation between the two time series – a strong positive correlation results in a slope close to zero, and a slope of two occurs when variables are uncorrelated (*Taylor et al., 2002*). *Taylor et al. (2002)* do not specify which slopes can be expected if the time series are negatively correlated. Logic dictates, however, that a slope greater than two can be expected for negative correlations and this is confirmed in Figure 3.5, which depicts the cumulative sums for various correlations. As is the case for the sliding correlations, the cumulative sums are not used to test the statistical significance of the results, but only to identify periods warranting further investigation. The cumulative sums are shown in the appropriate appendices.

3.3.3 Seasonal

To examine the seasonal aspect of any potential relationship, the correlations and cumulative sums are performed for individual months as well as three-monthly averages, such as JFM, FMA… and so on. There are a number of reasons to expect that the geomagnetic forcing of atmospheric circulation will have a strong seasonal signal. Pronounced seasonal variations are evident in indices of geomagnetic activity, which peak around the equinoxes (recall the analyses presented in Figures 2.14 and 2.15). Furthermore, upper atmospheric changes associated with magnetic storms also vary seasonally. Temperature changes are greatest in summer months, but relative density changes are most pronounced in winter months (*Prölss and Roemer, 2000)*. Similarly, the terrestrial atmosphere is dominated by seasonal patterns, such as the stratosphere-troposphere coupling during JFM in the northern hemisphere and November in the southern hemisphere (*Thompson et al., 2000*), described in later sections and chapter five, as well as seasonal cycles of solar irradiance and ozone concentrations.

Sun-weather studies, which focus on relationships between geomagnetic activity and the lower atmosphere at the daily level, frequently examine the seasonality of their results. Section 2.3.1 has already indicated that the many studies at this timescale claim that sun-weather relationships are strongest in winter. The seasonality of solar-climate relationships at annual or greater timescales, however, is not as well defined because most studies use either annual or daily data only. In doing so, they overlook an important dimension of the results and miss the potential insights that the seasonality of the results can provide for the identification of appropriate solar-climate mechanisms.

3.3.4 Spatial

At times when the magnitude and spatial pattern of the results is of interest, this study relies on the 'composite technique' (*Kodera et al., 1999*). This technique simply involves the averaging of a particular parameter for periods of high and low solar or geomagnetic activity and comparing the differences between the two averages. This procedure is used frequently in solar-climate studies (see, for example, *Bochníček et al., 1996, 1999*) to show spatial differences in atmospheric parameters between the extremes of solar activity. When using this technique it is important to consider the validity of the resulting averages – something that most researchers neglect. It is necessary to demonstrate that the differences seen in the results are not the result of chance. In this chapter, randomness was evaluated by performing composites using randomly selected data and using the magnitude of the resulting averages as an indication of the influence of stochastic variations on the results.

3.3.5 Lagged

There are a number of mechanisms that can potentially explain a link between geomagnetic activity and atmospheric circulation. The various temporal, seasonal, and spatial aspects of this link provide constraints on which mechanisms are suitable, and will be used in chapter five to help deduce how solar variations are manifested in the terrestrial atmosphere. One possible mechanism involves the propagation of atmospheric circulation anomalies in the middle or upper atmosphere, generated by solar and geomagnetic activity, to the lower atmosphere. The time required for such propagation to occur is unclear, but if lag is not incorporated into the analyses, a solar-climate relationship that requires this mechanism may not be detected. There are other reasons to suspect that an atmospheric response to geomagnetic activity may be delayed by a number of months. Ozone concentrations in the stratosphere are known to have a long 'memory', with variations persisting several months (*Thompson and Wallace, 1998*). Alternatively, if solar or geomagnetic activity influences the lower atmosphere through radiative forcing alone the thermal inertia of the oceans may introduce some lag into the relationship.

This chapter therefore calculates correlation coefficients between geomagnetic activity and the atmospheric circulation indices for various lags. For example, variations in the January Antarctic Oscillation are compared to geomagnetic variations for the previous December, then November… and so on. The lag is extended to eleven months, and the results are compared to the 'un-lagged' data.

3.3.6 Statistical Significance

One of *Pittock's (1978, 1979)* guidelines suggests that solar-climate researchers "critically examine the statistical significance of the result, making proper allowance for… autocorrelation and smoothing…". His recommendations have generally gone unheeded, and none of the solar-climate studies described in chapter two account for serial correlation. This is despite the fact that in some cases, such as *Friis-Christensen and Lassen's (1991)* solar-cycle length studies, the time series under consideration were highly smoothed.

In this study, serial correlation was taken into consideration when performing *t*-tests on correlation coefficients by replacing the actual number of observations with the effective number of observations (N_{eff}). N_{eff} is calculated as follows (modified from *Slonosky et al., 2000*):

$$N_{eff} = N \times \frac{(1 - |r_1 r_2|)}{(1 + |r_1 r_2|)}$$

where N is the total number of observations, and r_1 and r_2 are the lag-one serial correlation coefficients of the two time series under consideration. The original formula in *Slonosky et al. (2000)* does not use the absolute value of the lag-one serial correlations. In this study, it was found that the lag-one serial correlations for the atmospheric indices were sometimes negative, which lead to N_{eff} values that were greater than the original N. The use of the absolute values avoids this anomaly.

Recently, researchers in atmospheric science have followed factions in other quantitative and semi-quantitative fields by criticising the use of null hypothesis significance testing, citing the numerous problems associated with the dichotomous nature of such testing (*Nicholls, 2001*). These problems are exaggerated by the effect of serial correlation on sample sizes. For example, the geomagnetic AA index is serially correlated[41], even more so once it has been smoothed with a five-point moving average to highlight decadal variations. It stands to reason that if geomagnetic activity forces atmospheric circulation, then it too will be serially correlated. Therein lies the conundrum, because the stronger the forcing, the higher the serial correlation, and subsequently the lower the effective number of observations. Statistical significance becomes less likely the stronger the relationship becomes. This particular problem is especially pertinent to solar-climate studies, which often focus on long-term climate changes only, and perhaps explains why solar-climate researchers are reluctant to adopt Pittock's suggestions and do not account for serial correlation and smoothing in their analyses.

The traditional null-hypothesis significance tests, which are appropriate for the raw or interannual data but which might overestimate the impact of serial correlation for the decadal data, were therefore supplemented by randomisation tests using pseudo-random time series. The random time series were constructed by generating pseudo-random variations with similar spectral properties to the geomagnetic data. This is demonstrated in Figure 3.6, which shows the serial correlation functions for the real, detrended JFM

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[41] The JFM original AA index, from 1960 onwards, has a lag-one correlation coefficient of 0.49. For the smoothed JFM AA index, the lag-one coefficient is 0.88, while the lag-two correlation coefficient is 0.69.

AA index and the randomly generated time series. The figure shows that the serial correlation function of the two time series is very similar, especially at lag-one, which is the only value incorporated into estimates of N_{eff} as described previously. The spectral properties were extracted for the linearly detrended, smoothed AA index. Once the pseudo-random data were generated, a linear trend compatible with that of the original data was reinstated. The inclusion of the linear trend is required to approximate the serial correlation of the original AA index, but is also affords an opportunity to confirm that the correlations are not due solely to the presence of a trend in both time series.

The effective number of observations was calculated for one thousand permutations of the random time series to confirm that the N_{eff} of the random time series is similar to that of the original data. Correlations were then performed between each random time series and the atmospheric data, and the resulting coefficients were ranked according to magnitude. The statistical significance of the correlations was then based on the ranking of the real correlation, which is tantamount to the probability of achieving correlations of that magnitude if the null hypothesis is true. This procedure is only performed for specific correlations using decadal data, outlined in the results section. Diagrams of the distribution and range of the random versus the 'real' correlations are presented in later sections.

3.4 Results

3.4.1 The relationship between geomagnetic activity and the Antarctic Oscillation

Figure 3.7 shows the correlation coefficients between the raw, decadal, and interannual monthly data of the AA and SAM indices, while Figure 3.8 depicts the same correlations using three-monthly averages. The correlations are performed over the entire length of the available data – 1958 to 1999 for the raw data. Two years were lost from the end of the decadal and interannual time series due to the use of the five-point moving average in their derivation. Table B1 (in Appendix B) shows all the correlation results as well as the N_{eff} values used in the calculation of statistical significance.

Statistical significance was tested using Student *t*-tests, with α set to 0.05 in all instances.

Clearly evident in the results for the three-monthly averages, and to a lesser degree the monthly results, is a strong seasonal pattern with correlations peaking in March for the monthly data and February-March-April (FMA) in the three-monthly averages. Statistically significant correlations are evident for the raw and interannual variations of the FMA data (r = 0.43; N_{eff} = 29 and r = 0.52; N_{eff} = 38 respectively) and the interannual MAM data (r = 0.40, N_{eff} = 37). In the monthly data, statistically significant correlations are limited to the raw data for March (r = 0.39, N_{eff} = 38). Using r^2 values, it is evident that roughly 16% of the variability in the raw FMA and MAM data can be attributed to solar-modulated geomagnetic activity. Over 27% of the variability in the FMA interannual data of the SAM is associated with geomagnetic activity, as indicated by the r^2 value for the raw FMA correlation.

Figures 3.9 and 3.10 show the similarities between the raw and interannual variations of the AA index and the SAM for the FMA averages. Figure 3.10 shows that the relationship between the FMA interannual AA and SAM indices is weaker towards the beginning of the record, and this is supported by the cumulative sums shown in Figure 3.11. The cumulative sums show that the periods of strongest positive correlations generally occur after ~1971 and continue until the end of the record. The correlation coefficient between these indices for this period is 0.62. This value is statistically significant at the 95% confidence level (N_{eff} = 26), and using r^2 indicates that 38% of the recent (1971 onwards) interannual variations in the SAM can be attributed to solar activity. Graphs of interannual variations of the AA and the SAM indices for all other months and three-monthly averages are shown in Appendix B (Figures B1 and B2) and do not show any correlations of particular note beyond those already mentioned.

Charts of other cumulative sums for both the monthly and three-monthly interannual data are also provided in Appendix B (Figures B3 and B4). The graphs of cumulative sums show intervals of small deviations (*i.e.*, positive correlation) for January, February, March, and April and a period of large deviations (*i.e.*, negative correlations) for most other months and monthly averages around 1990. For most graphs, however, the slope does not deviate much from the gradient of two, associated with zero correlations and indicated by a stippled line, for any extended intervals. This indicates that the relationship between geomagnetic activity and the Antarctic Oscillation is largely restricted to the time intervals and months described in the previous paragraphs.

Although the statistically significant results are limited to the original and interannual variations, it is important to note that the decadal variations are highly correlated for FMA (r = 0.71; N_{eff} = 4, Figure 3.12) and, to a lesser extent, other three-monthly averages. The smoothing process used in the derivation of the decadal values enhances the high degree of serial correlation already present in the data, due largely to the cyclic nature of solar and geomagnetic activity. This serial correlation severely limits the effective number of observations – for the decadal variations N_{eff} ranges from three to six (see Table B1), requiring correlation values of 0.95 to 0.77 for statistical significance. The application of the null hypothesis significance test using N_{eff} is supported by the results of the permutation tests, which also reveal that this correlation is not statistically significant at the 95% confidence level. Using one-thousand permutations of pseudo-random time series exhibiting similar behaviour (trend, spectral characteristics, serial correlation and N_{eff}) to the FMA AA index the ρ-value for this correlation is only 0.145. This is demonstrated in Figure 3.13, which shows the distribution and range of the random correlations as well as the 'actual' correlation coefficient. Despite the lack of statistical significance, the results of the decadal correlations may be practically significant because a large proportion of the decadal variability in the SAM index can *possibly* be attributed to solar activity. Another interesting feature of the decadal correlations in the seasonal data is the second peak in correlation coefficients for the SON value (r = 0.59). The two peaks (FMA, SON) may be related to the equinoctial peaks in geomagnetic index magnitude described in section 2.2.4 (compare Figure 3.8 to Figure 2.15).

There is little scope for examining temporal patterns in the decadal correlations because of the limited record length of the Antarctic Oscillation index (1958-1999, N = 38). However, Figures 3.14 and 3.15, which show the 11-point sliding correlations between the decadal monthly and three-monthly SAM and AA indices, highlight some interesting periods. The results for the monthly and three-monthly sliding correlations are very similar and indicate that the positive autumnal correlations for the decadal variations, evident since the 1960s, do not extend to the present day. Figure 3.15, especially, shows that the positive correlations end in 1990 for the DJF through to the MAM seasonal averages. This is evident in Figure 3.12, which shows the FMA decadal variations in the SAM and AA indices from 1960 to 1997. Both exhibit maxima around 1975 and 1983, and minima around 1965, 1978, and 1985. However, after 1989 the two indices are negatively correlated. Limiting the correlation to the period of 1962 to 1989 increases the coefficient from 0.71 to 0.93. This latter correlation coefficient is significant at the 95% confidence despite the high degree of serial correlation ($N_{eff} = 4$), and it suggests that over 80% of the long-term variations in the SAM might be associated with geomagnetic activity, but that this relationship is temporally inconsistent.

Overall, these results suggest that, during the late austral summer/early autumn, geomagnetic activity influences atmospheric circulation in the southern hemisphere. Although this relationship is statistically significant for the interannual variations and not for the decadal variations, the correlation for the raw data is statistically significant for the FMA monthly average. Using r^2 it reveals that 18% of the variations in the SAM, from 1958 to 1999, can be attributed to solar-modulated geomagnetic activity. It must be conceded, however, that the relationship between geomagnetic activity and the Antarctic Oscillation is temporally and seasonally limited.

Lagged Results

Figure 3.16 shows the correlation coefficients for the lagged interannual data. The values shown on the x-axis correspond to the number of months lag between the geomagnetic AA index and the SAM index. For example, for the January plot a lag value of negative one indicates that the January Antarctic Oscillation index has been correlated to the December AA index of the previous year, negative two indicates November's AA index has been used … and so on. The correlations are calculated over the same interval as the un-lagged data, 1960 onwards. The results hint at a delayed response between geomagnetic variations and southern hemisphere atmospheric circulation that spans several months. Statistically significant correlations, at the 95% confidence level, occur at progressively larger lags from February onwards. These are marked on Figure 3.16 by solid circles. For instance, the interannual variations of the February Antarctic Oscillation are significantly correlated to the January AA index (r = 0.34; N_{eff} = 37). The March Antarctic Oscillation index also correlated best to the January AA index (r = 0.33; N_{eff} = 37). Statistically significant correlations are not evident for the April data at any of the observed lags, but the May data correlates significantly at lags of negative two and negative four. The correlation at negative four links the May Antarctic Oscillation to the January AA index (r = 0.34; N_{eff} = 37). Progressing one month forward to June, statistically significant correlations occur at lags of negative three and negative five. The lag at negative five (r = 0.43; N_{eff} = 37) links the June SAM and January AA indices. Similarly, July exhibits significant correlations at lags of negative six and negative four. This pattern skips August and October, but is evident in July and September. SAM indices for the latter months correlate best and persistently to the January or February AA indices.

The results for the decadal data are shown in Figure 3.17. A similar pattern of high correlations occurring at lags that relate to January or February AA indices is evident. However, once serial correlation has been accounted for there are no statistically significant correlations for any of the lagged correlations in the decadal data.

3.4.2 The relationship between geomagnetic activity and the Arctic Oscillation

Table 3.1 indicates that correlations between geomagnetic activity and the NAM index are extremely low over the period 1899-1999. Therefore, sliding correlations were again performed for the monthly and three-monthly averages and are shown in Figures 3.18 and 3.19. From 1965 onwards there are consistently strong positive correlations for the boreal winter months (December, January, February, March) and three-monthly averages from NDJ to MAM. Once again, the correlations are stronger for the three-monthly averages than the monthly data. This is illustrated in Figures 3.20 and 3.21, which show correlation coefficients for the raw, decadal, and interannual AA and NAM data. The correlation coefficient values and the accompanying N_{eff} values are shown in Table B2 in Appendix B. Once again, all *t*-tests were performed with α set to 0.05.

In the monthly data, statistically significant correlations are evident for the raw (r = 0.62; N_{eff} = 28) and interannual (r = 0.49; N_{eff} = 33) January indices. Statistically significant correlations also occur in the raw indices for all seasonal averages from NDJ to FMA, as well as the interannual variations for NDJ, DJF and JFM. The correlations for JFM are consistently greater than those for any other seasonal average, and the indices involved are shown in Figures 3.22 (raw), 3.23 (interannual), and 3.24 (decadal). The correlation for the raw JFM data is 0.66 (N_{eff} = 25) and for the interannual data is 0.58 (N_{eff} = 32).

Table 3.1. Correlation coefficients between the NAM and geomagnetic activity (1899-1999). The correlations are for the entire length of the NAM index, and indicate that there is no statistical relationship between solar activity and atmospheric circulation for that period. This chapter examines the temporal nature of possible relationships, and reveals that there are specific, climatically important periods for which the geomagnetic AA index is related to atmospheric circulation.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
r(NAM,AA) 1899-1999	0.06	0.05	0.00	-0.04	0.04	0.14	0.15	0.06	0.02	0.01	0.03	0.08

The correlation coefficients shown in Figures 3.20 and 3.21 were calculated for the period highlighted by the sliding correlations of the decadal variations (that is, 1965 onwards). An examination of the temporal nature of the interannual variations (Figures B5 and B6, which show the cumulative sums, in Appendix B) reveals a similar pattern. Except for the graphs for January and the JFM monthly average, the slopes of the cumulative sums in all other graphs do not deviate much from the slope for uncorrelated data, indicated in the graphs by a stippled line. The JFM graph shows a period of positive correlations commencing shortly after 1960, that becomes stronger after 1970. The January graph reveals a period of positive correlations from 1960 onwards, supplemented by a limited interval of positive correlations between 1940 and 1950. This indicates that correlations for the interannual data exhibit a similar temporal and seasonal pattern as the decadal data. The lack of correlations for other months and monthly averages are evident in the graphs of the interannual variations of the AA and NAM indices, shown in Figure B7 to B10 (in Appendix B).

Although not statistically significant due to the effect of serial correlation on N_{eff}, the correlation coefficients for the decadal averages may have practical significance. This is particularly true for the January (r = 0.82; N_{eff} = 4) and the JFM (r = 0.79; N_{eff} = 4) data, which is highly correlated. When the statistical significance of these results was tested using the permutation tests described earlier both were found to be statistically significant (ρ = 0.002 and 0.005 respectively). The distribution of the random correlations, as well as the 'actual' correlation, is shown in Figure 3.25. It is therefore possible to assert that, for these months, over 60% (r^2) of the long-term, decadal variations in atmospheric circulation in the northern hemisphere can be attributed to geomagnetic activity.

The sliding correlations (Figures 3.18 and 3.19) also reveal a period of negative correlations in the AMJ and MJJ averages from ~1942 to 1985. However, correlations between original, decadal, and interannual indices for this period are not statistically significant and are quite low. The correlations for the interannual data are, in fact, positive, while the decadal correlations are negative. Figures 3.26 and 3.27 show the limited relationship between the interannual (r = 0.25) and decadal variations (r = -0.60) of the AA index and the MJJ average of the NAM index, especially when compared with the high correlations for the DJF AA-NAM indices. The decadal variations are quite similar, however, for some periods, especially around 1960 and in the 1980s, but the overall impression is that the correlations for this earlier period are coincidence.

Overall, the results suggest a statistically and practically significant solar influence on atmospheric circulation in the northern hemisphere. Like its southern counterpart, the relationship has a seasonal structure. In the northern-hemisphere data, high correlations are limited to boreal winter months and seasonal averages. The magnitude of the relationship is stronger in the northern hemisphere than in the southern hemisphere. The proportion of the variance in northern hemisphere atmospheric circulation explained by geomagnetic activity, based on r^2 for the raw JFM indices from 1965 onwards, is 44%.

Lagged Results

The lagged correlation coefficients for the interannual data, shown in Figure 3.28, do not show any consistent patterns suggesting either a fixed delay between geomagnetic variations and the NAM or a variable delay centred on a particular month. Once again, the same period as the previous section (1965 onwards) has been used in the lagged correlations. Although statistically significant correlations are scattered throughout the lagged results, the only noteworthy features are found in the February and March graphs. Both show increased and statistically significant correlations at negative one to negative three months lag. The correlations are especially high for the March data at one months lag ($r = 0.70$; $N_{eff} = 28$; $\alpha = 0.05$) – shown in Figure 3.29.

The results for the decadal data, shown in Figure 3.30, are generally insignificant (statistically) and do not suggest a lagged relationship between geomagnetic activity and the NAM.

Comparison to the North Atlantic Oscillation

The results for the North Atlantic Oscillation are very similar to those for the Arctic Oscillation. This is not surprising, given that the two oscillations relate to a similar (if not the same) phenomenon. When calculated over the same period as the NAM Index (1965 onwards), the correlations for the NAO index are generally higher. The most prominent difference is the magnitude of the correlations for the decadal January (r =0.90; N_{eff} = 5) and JFM (r = 0.90; N_{eff} = 4) data, both of which are statistically significant at the 95% confidence level despite the effects of serial correlation. Correlation coefficients for other months and monthly averages are shown in Table B3 in Appendix B.

Correlations between the three-monthly averages of the AA index and the raw, decadal, and interannual variations of the two nodes of the NAO index are shown in Figures 3.31 and 3.32. The figures, based on data from 1965 onwards, show strong correlations for both the Ponta Delgada and Iceland sea level pressure records in the winter months, especially JFM. The raw variations for the both Ponta Delgada and Iceland records, for the JFM averages, are both significantly correlated to geomagnetic activity (r = -0.68; N_{eff} = 32 and r = 0.62; N_{eff} = 30, respectively). The N_{eff} values associated with these, and other, correlations are shown in Table B4 (Appendix B). The correlations provide evidence that geomagnetic activity can have an impact on climate at the earth's surface.

3.4.3 Spatial Patterns

The spatial pattern of the relationship between geomagnetic activity and the SAM and NAM can be shown by calculating the differences in sea-level pressure between years of high and low geomagnetic activity, as described in the methods section. The sea level pressure data are from the *NCEP/NCAR* reanalysis dataset (*Kalnay et al., 1996*) and were obtained from the *NOAA CDC* web page[42]. Differences for the month of January are shown in Figure 3.33a, and differences for March are shown in 3.33b. Figure 3.33c shows the differences in sea level pressure, for the month of January, between two sets of five randomly chosen years. This reveals the magnitude of stochastic sea level pressure differences that occur independently of geomagnetic activity variations. This latter panel (3.33c) indicates that the changes shown in Figures 3.33a and 3.33b are larger than what can be expected by chance alone.

In Figure 3.33a, the mean January sea level pressure values for five years of low decadal AA index values (1964, 1965, 1966, 1967, 1968) were subtracted from five years of high decadal AA index values (1973, 1974, 1990, 1991, 1992). January was chosen because it corresponds to the time when the AA-NAM relationship is strongest. The average AA value ranged from 16.7 nT to 25.6 nT between the years of low and high geomagnetic activity. The largest differences occur in the North Atlantic. On a decadal timescale, sea level pressure around the Icelandic low varies by as much as 16 hPa. Further south, around the Azores high, sea level pressure can vary up to 9 hPa between extremes of geomagnetic activity. The higher difference around Iceland explains why correlations are higher between geomagnetic activity and the NAO index

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[42] *NOAA-CIRES Climate Diagnostics Center*, http://www.cdc.noaa.gov/cdc/reanalysis

(which uses station based data) than they are with the EOF based NAM-index that does not capture such disparate variations as well.

Figure 3.33a not only quantifies the changes associated with the geomagnetic forcing of atmospheric circulation, but also reveals that significant changes are restricted to the North Atlantic. No significant changes (that is, of a magnitude that exceeds those found for the random data in Figure 3.33c) are evident over the Pacific or the tropical/equatorial regions. The changes in sea level pressure associated with extreme of geomagnetic activity match those of the North Atlantic Oscillation, as expected from the results of the previous section. This indicates that the influence of geomagnetic activity on atmospheric circulation (and surface pressure) in the northern hemisphere is accomplished basically through processes that affect only the Arctic and North Atlantic Oscillations.

Figure 3.33b shows the sea level pressure differences for the month of March. March was chosen to show the spatial pattern associated with the AA-SAM relationship in the southern hemisphere. In this case, the years of low decadal AA index values were the same as the January years (1964-1968), but years of high AA values ranged from 1989 to 1993. The AA values averaged 18.5 nT and 35.2 nT for the 'low' and 'high' years respectively. Although the magnitude of the AA index differences is greater for the March averages than the January averages, the sea level pressure signature is much smaller. The largest changes are restricted mainly to the southern high latitudes, between 150°-210° longitude. Within this spatially limited region, changes in sea level pressure between high and low decadal AA averages range up to 15 hPa. The comparison of Figures 3.33a and 3.33b indicate that the magnitude of the largest sea level pressure changes between low and high values of geomagnetic activity is similar in both hemispheres, and averages roughly 16 hPa.

Figures 3.33a and 3.33b demonstrate that increased geomagnetic activity is associated with a decrease in sea level pressure in the high-latitude southern hemisphere and with the intensification of the Icelandic and Azores pressure systems in the northern hemisphere. It is important to note, however, that the sea level changes shown in Figure

3.33 do not represent the full extent of the climate change associated with either geomagnetic activity or the atmospheric oscillations described here.

3.5 'Sunspot' forcing of atmospheric circulation

Bucha and Bucha have already demonstrated that NAO correlates to geomagnetic AA index but not the sunspot number. Similar results are expected in this section, which expands upon the study of Bucha and Bucha by examining the temporal and seasonal aspects of any possible sunspot-circulation relationship, and by incorporating the southern hemisphere. The seasonal and temporal correlations presented in this chapter are similarly diminished when the sunspot is used in place of the AA index, raising two possibilities:

1. Indices of geomagnetic activity, such as the AA index, are more appropriate solar activity proxies than the sunspot number, and that solar forcing of the lower atmosphere occurs directly through changes in solar irradiance.

2. Or, sunspot activity may be a useful proxy of solar irradiance changes only, while geomagnetic activity represents a broader range of solar activity and terrestrial variations, as outlined in chapter two. These include changes in the upper atmosphere associated with geomagnetic storms and the relationship between cosmic-ray flux and geomagnetic activity. It may be that one of these other solar-terrestrial links is a more appropriate solar-climate mechanism (see sections 2.2.2 and 2.2.3).

Figures 3.34 and 3.35 show monthly and three-monthly average correlations between the original, decadal, and interannual variations in the SAM index and sunspot number. The calculations are performed over the entire record length, in the same manner as the AA-SAM correlations described earlier in this chapter. Correlation coefficients for all months and three-monthly averages and the effective number of observations in each case are shown in Table B5 (Appendix B). The correlations are consistently lower when the sunspot number is used. Only two statistical significance correlations are evident. These include the original variations for the month of June ($r = 0.32$; $N_{eff} = 40$) and the interannual variations of the JFM average (r = 0.33; N_{eff} = 35). Similar results are evident when the sunspot number is correlated to the NAM index – Figure 3.36 and 3.37, and Table B6 in Appendix B. The correlations are consistently very low relative to the AA-NAM results. Significant correlations are limited to interannual variations for February (r = 0.36; N_{eff} = 32) and the JFM average (r = 0.36; N_{eff} = 30). For the JFM average the corresponding AA-NAM correlation is substantially higher (r = 0.58).

For the purpose of comparison, the correlations described above were performed for the same periods as the corresponding AA correlations. It is possible, however, that any relationship between the sunspot number and atmospheric circulation would have a different temporal pattern. This was investigated in the same manner as the AA correlations – using sliding correlations for the decadal variations. Figures 3.38 and 3.39 show the 11-point sliding correlations between the decadal monthly sunspot number and the SAM and NAM indices. No periods of particular note are evident for either atmospheric oscillation. Indeed, the sliding correlations for both are generally fragmented and inconsistent.

Correlations calculated using the AA index as a proxy for solar activity (Figures 3.7 and 3.19) are much greater than those that are calculated using the sunspot number (Figures 3.35 and 3.37). This demonstrates that a solar-climate relationship is evident only when geomagnetic activity is used as an indicator of solar activity. Accordingly, the practice of using the sunspot number (or the closely related 10.7 cm solar flux) as an indicator of solar activity may limit the magnitude of solar-climate relationships and lead researchers to dismiss solar forcing of climate in the lower atmosphere.

3.6 The role of the QBO

When describing links between the solar cycle and the lower atmosphere, much of the modern literature indicates that the quasi-biennial oscillation (QBO) plays an important role, modulating solar-climate relationships based on the direction of the QBO phase (*Krzyścin,* 1995*; Soukharev, 1997; Labitzke and van Loon, 2000*). *Labitzke and van Loon (2000)*, in particular, described the effect of the QBO on solar cycle forcing of the stratosphere. This effect has been described briefly in section 2.2.10 and is largely restricted to the northern hemisphere. *Labitzke and van Loon (2000)* noted that correlations between stratospheric geopotential heights and temperatures in the Arctic were positive during the QBO west phase, negative during the QBO east phase, and non-existent when the data are not separated according to the QBO phase.

There is, therefore, strong support for the suggestion that the QBO phase is relevant to solar-climate relationships. It is not clear, however, if geomagnetic forcing of the lower atmosphere is also contingent on the phase of the QBO. The analyses so far in this chapter have yielded statistically significant, relatively robust results without any consideration to the QBO, demonstrating that it is not necessary to incorporate the QBO for a geomagnetic activity signature to be detected in atmospheric circulation. Nevertheless, the inclusion of the QBO may improve the results, especially since *Bochníček et al. (1996, 1999)* describe a different response in northern hemisphere tropospheric temperature and pressure to geomagnetic activity, depending on the phase of the QBO.

Accordingly, the correlations between interannual variations in geomagnetic activity and both the Antarctic and Arctic Oscillation indices were recalculated, this time with the data separated according to the phase of the QBO. The data for the QBO, which consist of equatorial 30 hPa zonal wind values, were provided by Barbara Naujokat and obtained from the *Joint Institute for the Study of the Atmosphere and Ocean (JISAO)* website[43]. The derivation and history of the QBO zonal wind index are described by *Naujokat (1986)* and *Marquardt and Naujokat (1997)*. For both atmospheric indices, only values from 1965 onwards were used in the calculations. The results are shown in Figures 3.40a and 3.40b. The number of observations in each calculation in these figures is shown in Table 3.2.

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[43] http://tao.atmos.washington.edu/data_sets/qbo/

Table 3.2. The correlation coefficients between the interannual variations of the SAM and NAM indices and geomagnetic activity, separated according to the phase of the QBO, from 1965 onwards. The table also shows the number of observations in each correlation and statistically significant correlations are in bold. These results are discussed in the text.

SAM	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
R(AA,SAM) QBO+	-0.34	-0.25	0.24	0.12	0.07	-0.63	0.21	0.39	0.31	0.14	0.12	-0.30
Number of Observations	18	18	18	20	16	12	11	14	15	14	15	14
R(AA,SAM) QBO-	0.28	0.14	0.35	0.28	0.10	-0.15	-0.33	-0.31	0.17	-0.27	-0.27	0.08
Number of Observations	15	15	15	13	17	21	22	19	18	19	18	19
NAM	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**
R(AA,NAM) QBO+	0.29	0.00	0.03	0.00	0.33	0.35	0.26	-0.21	-0.14	0.04	**0.53**	0.28
Number of Observations	18	18	18	20	16	12	11	14	15	14	15	14
R(AA,NAM) QBO-	**0.71**	0.24	0.35	0.09	0.29	-0.03	0.02	-0.09	0.03	-0.39	-0.09	0.12
Number of Observations	15	15	15	13	17	21	22	19	18	19	18	19

For the SAM there is generally little improvement in the magnitude of the correlations, with the exception of June. During the QBO west phase (positive QBO values) the June geomagnetic AA index and the Antarctic Oscillation are well correlated (r = -0.63, N = 12). This correlation coefficient is much larger than the corresponding correlation for the QBO east phase (r = -0.15, N = 21), and larger than the correlation coefficient for both indices when the QBO phase in not considered (r = -0.21, N = 33) and it is statistically significant despite the limited number of observations. Other months show varying, minor correlations that have achieved a higher magnitude than the original correlations simply because N has been reduced considerably. There is no improvement in the correlations for March under either phase of the QBO.

Conversely, the results for the NAM indicate that the QBO has a major role in geomagnetic forcing of northern hemisphere circulation. Geomagnetic activity forcing of the NAM during January shows a marked improvement when separated according to the phase of the QBO. During the QBO east phase the correlation coefficient between geomagnetic activity and the Arctic Oscillation index, from 1965 onwards, is 0.71 (N = 15). This value is statistically significant at the 95% confidence level. The corresponding QBO west phase correlation is only 0.29 (N = 18) and is not statistically significant at the 95% confidence level. Interannual variations of the geomagnetic AA index and the NAM index are shown separately for the QBO east (Figure 3.41a) and west phase (Figure 3.41b). The original correlation coefficient for January is 0.49, which although statistically significant, is considerably less than the QBO east results. It must be considered, however, that the number of observations in the QBO east phase correlations has been reduced by 15 compared to the original correlations. Accordingly, some of the increase in magnitude will be due to the smaller N. January values of the surface pressure records for the NAO nodal stations were also separated according to the phase of the QBO and correlated to the AA index. The results are shown in Table 3.3, and indicate that a negative QBO index strengthens the correlations. Correlation coefficients for the Iceland record increase from -0.33 for the unseparated data to -0.53 for the QBO east phase data. Similarly, the correlation coefficient between the Ponta Delgada record and geomagnetic activity is increased from 0.26 to 0.66 when limited to the QBO east phase. In both cases, the number of observations involved in the restricted correlations is less than half of the original N, but it can be argued that the increase in correlation coefficients is not solely the result of the reduced number of observations because the QBO west calculations also feature few observations but yield lower results.

For the NAM data, there is also some improvement in the correlation results when the November calculations are performed for QBO west data only. The magnitude of the improved correlation ($r = 0.53$; $N = 15$) is statistically significant at the 95% confidence level. The reality of this correlation, as well as others, is examined in chapter five.

By separating the annual data into the phases of the QBO, it has become evident that the already significant January correlations between geomagnetic activity and the NAM are much improved. In fact, the results suggest that at the annual level the relationship is restricted to months in which the QBO is eastward. Using the raw January AA and NAM indices yields a very strong, statistically significant relationship for the QBO east phase ($r = 0.85$, $N = 16$), especially when compared to the QBO west results ($r = 0.38$, $N = 18$). This is also an improvement on the unseparated data ($r = 0.62$, $N = 35$). The improvement in AA-SAM correlations in June is unexpected, largely because the correlations using the raw, decadal, and interannual data without the QBO phase were unremarkable. Chapter five, which examines possible mechanisms for the relationships described within this chapter, considers the implications of the QBO modulation of geomagnetic forcing and checks the validity of the findings in this chapter.

Table 3.3. Correlation coefficients between the January AA index and January surface pressure records for the NAO nodal points, separated according to the phase of the QBO, 1965 onwards. The correlations are higher under QBO east phase conditions.

	Iceland (1965-1997)	Ponta Delgada (1965-1995)
r(Jan AA, surface pressure) QBO west	-0.13	-0.23
Number of observations	18	17
r(Jan AA, surface pressure) QBO east	-0.53	0.66
Number of observations	15	14
R(Jan AA, surface pressure) QBO both	-0.33	0.26
Number of observations	33	31

3.7 Discussion

The results presented within this chapter provide numerous insights into the influence that geomagnetic activity has on atmospheric circulation. These findings have expanded upon the research of *Bucha and Bucha (1998)* and described the temporal, seasonal, and spatial aspect of the link between geomagnetic activity and the Arctic (and North Atlantic) Oscillation. It has also provided what is perhaps the first examination of the importance of geomagnetic activity to the SAM, and revealed that a geomagnetic activity signature is also found in the southern hemisphere.

There is a strong temporal and seasonal signal in the relationship. Since the 1960s, geomagnetic activity can explain ~18% of the variability in the SAM from February through to April, and ~44% of variations in the January-to-March averages of the NAM. When restricted to QBO east Januaries, over 70% of the variability in the NAM can be attributed to the geomagnetic AA index. While the geomagnetic activity signature in the northern hemisphere, during January, is modulated by the QBO, the QBO does not feature strongly in the corresponding relationship in the southern hemisphere. This is an early indication that, while the stratosphere may play an important role in the northern hemisphere relationship, it may not be relevant to geomagnetic forcing in the southern hemisphere.

The seasonality of the results conflicts with the generally held view that solar-climate relationships are strictly a winter phenomenon. This is especially evident when the southern hemisphere seasonality is considered – the greatest results occur during autumn. Analyses for the northern hemisphere performed with monthly data indicate that the geomagnetic forcing of the Arctic Oscillation is primarily a January phenomenon, and is not as strong during the later winter (*i.e.*, February and March). The seasonality of the results suggests that analyses using only annual data will underestimate, or completely overlook, these relationships.

It is also significant that the relationships occur at interannual, as well as decadal, timescales. It is uncommon for solar-climate studies to consider annual timescales, largely because most indices of solar activity do not contain variability at that timescale. The implications of this are that the interannual relationships have greater potential for explaining or predicting climate change than decadal relationships alone. The fact that the relationships are evident at annual timescales also assists with the statistical significance of the results. Throughout this chapter it was found that serial correlation seriously limited the effective number of observations, and consequently the statistical significance of the results. Although the randomisation tests performed within this chapter suggest that the use of the effective number of observations may be overestimating the effects of serial correlation, it is always difficult to present decadal (or interdecadal) relationships as significant. The interannual results are not limited by serial correlation, and are therefore more reliable than the decadal results.

The findings of this chapter differ to those of *Thejll et al. (submitted 2002)*, which examines geomagnetic forcing of the NAO. The fact that prominent solar and climate researchers are examining this concept is a testament to its importance for recent climate change, but there are significant differences between the findings of this study and that of *Thejll et al. (submitted 2002)*. First, *Thejll et al.* use sliding correlations with 31-year intervals to examine temporal patterns. Such a coarse interval width has led them to misinterpret the temporal aspect of the relationship, and subsequently they suggest that the relationship between geomagnetic activity (which they parameterise by the Ap index, not the AA index) and the NAO begins in 1973. This is a whole decade later than the onset found in this thesis, which uses a much narrower interval for sliding correlations.

Furthermore, they use seasonal, rather than monthly averages, and they therefore assume that the geomagnetic forcing of the NAO is a winter phenomenon. Monthly analyses in this chapter indicate that it is an early winter phenomenon, and more specifically, that the correlations only occur in January. They use cross-coherency analysis to report that the correlation "…is driven by variability on time-scales of 7-10 years.". By analysing the relationship for decadal and interannual timescales separately, this chapter has indicated that the correlations occur both at the annual level and at the decadal level. The annual aspect of the correlation is one of the most important findings of this thesis, because it indicates that the relationship has practical significance. If the relationship only occurred at longer timescales, the total variance in the NAO attributable to geomagnetic activity would be low. They also do not incorporate the QBO into their analyses, which in this chapter was found to have a large bearing on the correlations. The QBO modulation of the relationship also has some bearing on potential mechanisms.

Despite all these differences, the overall result is the same in that now that a strong link has been established between solar-modulated geomagnetic activity and atmospheric circulation, it is important to focus on understanding how this link comes about (chapter five).

3.7.1 Implications

The results of this chapter can potentially explain many features of recent climate change. For instance, *Tourre et al. (1999)* described a quasi-decadal frequency in sea surface temperature and sea level pressure variability in the Atlantic Ocean with a frequency of around 11.4 years. They presented a figure showing that, in the past century, variations at this frequency only occur after 1960 (see their Figure 1b), and indicated that it represents an extension of the North Atlantic Oscillation. *Cavalieri and*

Häkkinen (2001) also note strong decadal variability in northern hemisphere sea level pressure planetary wave phase and a breakdown of the dominant wave pattern since the 1960s. Similarly, *Venegas and Mysak (2000)* note a change in sea ice concentrations and sea level pressures in the North Atlantic between 1950 and 1960. Decadal variations in both of these climatic parameters are evident from 1960 onwards, but are predominantly a winter phenomenon. *Venegas and Mysak (2000)* report that the decadal sea level patterns are "reminiscent" of the NAO and Arctic Oscillation teleconnection patterns. Through the analysis of northern hemisphere 500 hPa geopotential heights, *Knox et al. (1988)* raised the possibility of a climatic jump around 1962 which marks the abrupt beginning of a different climate regime. The coincidence of the decadal periodicity, the temporal pattern beginning in 1960s, and the association with the North Atlantic Oscillation, are very suggestive that geomagnetic activity is manifested in Atlantic climate through its correlation to the Arctic and North Atlantic Oscillations.

The results also have implications for the understanding of the Arctic and North Atlantic Oscillations, especially the positive trend evident in both indices since the 1960s. *Wunsch (1999)* observed similar periods of non-stationarity in a synthetic North Atlantic Oscillation time series, and suggested that the recent trend may simply be stochastic. Similarly, *Slonosky et al. (2000)* concluded that, when examining 200-year records of atmospheric circulation over Europe, the recent trend in the NAO index "does not appear unusual" (page 1875). However, the fact that the recent trend in the NAO index is not unprecedented (*Slonosky and Yiou, 2001*) does not warrant the conclusion that it is internally generated by the stochastic nature of the NAO, and not the result of external forcing.

Furthermore, *Gillett et al. (2000)* found that their general circulation model[44] did not simulate the recent trend observed in the winter NAM index when forced with greenhouse gas, sulphate aerosol, and ozone depletion changes. Although this can be explained, in part, by the limitations of the general circulation model used in their study, their findings suggest that another factor may be behind the NAM/NAO trend. The

[44] HadCM2

results of this chapter support the suggestion that solar-modulated geomagnetic activity is part of the cause of the recent trend in the atmospheric circulation indices. Figure 3.42 compares the magnitude of the correlations between the AA and NAM indices with the magnitude of the trend in the NAM index (from *Thompson et al., 2000*) for each month.

The figure shows that the magnitude of the trend in the NAM index, from 1968-1997, is proportional to the magnitude of the correlation between decadal variations of the AA and NAM indices for a similar time interval (1965-1997). The correlation coefficient between the monthly AA-NAM correlations and the monthly NAM trends is 0.71. The relationship is especially evident for months for which the NAM trend is significant at the 95% confidence level, January to March, which coincide with the three-monthly average (JFM) corresponding to the highest NAM-AA correlations. *Moritz et al. (2002)* note that despite recent advances in the understanding of the Arctic Oscillation, the source of the trend remains unclear. The results presented here are a testament to the practical significant of solar-climate relationships, since at least part of the trend can be ascribed to geomagnetic activity.

Incorporating the findings of *Feldstein (2002)* into this study further supports both the reality and the importance of this link. By comparing the trend and variance of the winter NAM for the 1899-1967 period to that of the 1967-1997 period, *Feldstein (2002)* concludes that the interannual variability for the earlier period is derived from climate noise (*i.e.*, internal forcing), and the latter period is characterised by external forcing. *Feldstein (2002)* associates the external forcing with either hydrosphere/cryosphere coupling to the atmosphere or a source external to the climate system, such as changes in stratospheric aerosol or ozone concentration. It is evident that solar-modulated geomagnetic activity represents the external process that has forced part of the recent changes in the NAM and NAO.

3.7.2 Pittock's guidelines

Have the analyses performed here complied with Pittock's guidelines (outlined in section 2.2.13)? In all, Pittock outlined eight guidelines for solar-climate researchers, though there is often some overlap between them. In the first guideline, Pittock emphasises the need to understand the properties of the data, and subsequently (guideline two), to choose appropriate methods for the analysis of the data. This was discussed in section 3.3, which explicitly listed the reasons for the different statistical approaches used in this chapter. Similarly, Pittock's third guideline, which calls for the critical examination of statistical significance, is addressed in this study with the use of N_{eff} in *t*-tests and also the use of randomisation tests.

The fourth guideline calls for the results to be tested in one or more independent data sets or subsets of the original data. This was achieved with the use of the NAO index, which complements the results based on the NAM. Similarly, the use of the southern hemisphere counterpart of the NAM, the SAM, fulfils this criterion because it validates the results for the northern hemisphere. Furthermore, a geomagnetic activity signature was also found in the surface pressure records for the two nodal points of the NAO, which can be considered as subsets of the original NAM data.

Pittock's fifth guideline is an important one, and is one that is often neglected by solar climate researchers. It calls for a hypothesis regarding the physical mechanism linking solar variability to climate that can be tested. This guideline is not fulfilled in this chapter, but is addressed in chapter five.

Guideline six requires an estimate of the practical significance of the results – this is provided by r^2 values and has also been explored in a non-quantitative way in section 3.7.1. The r^2 values are high enough to address *Pittock's (1978)* concern that the effects of solar variability on climate may not be large enough to have practical importance to climate research.

Guideline seven is very much a repetition of the first two, while the eighth guideline, which warns against the overstatement of the "statistical and practical significance of the results" (*Pittock, 1978*), is adhered to in this chapter, which has acknowledged the spatial, seasonal, and temporal limitations of the relationship.

3.8 Conclusions

This chapter has presented, for the first time, evidence that geomagnetic activity influences atmospheric circulation through its influence on the annular modes in both hemispheres. A statistically robust relationship is found that implicates geomagnetic activity in recent climate change, especially in the northern hemisphere. The relationship therefore has statistical and practical significance and supports the view that solar-climate studies are worth pursuing.

Based on the results so far it is possible to conclude that interannual variations in the winter NAO index are not climatic or meteorological noise, but are in part due to geomagnetic activity. This is especially evident during the east phase of the QBO. It is also possible, at least from the early 1960s onwards, to relate the recent trend in the NAM index, as well as the previously unexplained decadal variations, to the actions of solar-modulated geomagnetic activity. A similar temporal pattern is evident in the relationship between geomagnetic activity and southern hemisphere circulation, indicating that solar activity has a global impact on the lower atmosphere. The QBO does not feature strongly in the southern hemisphere relationship, and the seasonality of the results is different.

This chapter has also demonstrated that it is worthwhile examining existing solar climate relationships with extra scrutiny. In particular, examining the relationships at different timescales and considering the spatial, temporal, seasonal, and lagged aspects of the relationship can provide valuable insights into some of the unanswered questions within this field. The next chapter continues the investigation of the geomagnetic forcing of atmospheric circulation by examining daily timescales.

4 Geomagnetic activity and atmospheric circulation - Daily timescales

4.1 Introduction

The previous chapter has outlined an interesting and, to some extent unusual, relationship between annual and decadal variations in geomagnetic activity and indices of atmospheric circulation, such as the Antarctic and Arctic Oscillation. The aim of this chapter is to extend the analysis of the relationship to the daily timescale. Accordingly, this chapter uses the superposed epoch analysis technique to examine if geomagnetic and solar flare activity impact upon the Antarctic and Arctic oscillations.

Some researchers (for instance, *Bochníček et al., 1999; Tinsley, 1986*) have suggested that more work is required on solar-climate relationships at daily timescales. An understanding of the influence that geomagnetic (or solar flare) activity has on tropospheric circulation on a day-to-day basis is of great practical value. Not only would such an understanding have a practical application in weather forecasting, it would also help resolve some of the inconsistencies in the field of solar-weather studies. These inconsistencies have been outlined in chapter two and include the uncertainties surrounding the seasonality of the results and the lack of uniformity in the response time between atmospheric parameters to solar forcing (recall Table 2.5).

When coupled with the results from the previous chapter, however, an understanding of the day-to-day nature of solar-climate relationships has even greater potential because it can provide insights into possible mechanisms. To that end, the analyses performed in this chapter cover a time interval large enough to allow for possible mechanisms that involve stratosphere-to-troposphere propagation over a number of weeks.

4.2 Data and methods

Daily indices of the SAM and NAM were obtained from the *NOAA Climate Prediction Center* web page[45]. The daily SAM index begins on January 1st, 1979 and ends on the December 31st, 2001, and therefore contains 18,993 observations. The daily NAM index contains 8,401 observations; it begins on January 1st, 1950 and ends on December 2001. Two indices of solar activity were used in this chapter – a daily version of the geomagnetic AA index and a solar flare index. Both were obtained online from the *NOAA NGDC Solar Terrestrial Physics Division* web page[46]. Like its yearly counterpart, the daily AA index begins in 1868 and ends in 1998. The solar flare index data used in this study are calculated by T.Atac and A.Ozguc from Bagazici University Kandilli Observatory, Istanbul, Turkey, and begin on January 1st, 1976. Refer to chapter two for a description of both these indices.

The superposed epoch analysis technique was employed to determine if solar events, at the daily timescale, are manifested in indices of atmospheric circulation. Although the use of the superposed epoch analysis technique is ubiquitous in ‘sun-weather’ studies the manner in which it has been applied is often unclear. The basic assumption behind this technique (already described in section 2.2.6) is that by averaging numerous intervals of the same data around specific key dates, ‘noise’ in the data is averaged out and a response, consistent in time with regard to the key data, will remain.

In the data preparation stage, atmospheric indices were ‘detrended’ by subtracting the 91-point moving average from the original daily data. This was done so that any long-term trends in the data do not confound the superposed epoch analysis results, and so that the seasonal signal in the daily data does not skew the averages.

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[45] http://www.cpc.ncep.noaa.gov/products/precip/Cwlink/all_index.html
[46] The geomagnetic data are from:
http://www.ngdc.noaa.gov/STP/SOLAR_DATA/RELATED_INDICES/AA_INDEX/
and the solar flare data are available at:
ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_FLARES/INDEX

4.3 Statistical significance

The distribution of both detrended indices (the SAM and NAM indices) was examined using an Anderson-Darling test, which is a form of empirical distribution function statistical test (*Stephens, 1974*). In both instances, the data were found to be slightly non-normal. Histograms of both the daily annular modes are shown in Figures 4.1 and 4.2. The distribution of the data can have an important impact on significance tests. *Haurwitz and Brier (1981)* caution that if the response index is not approximately normal then parametric tests are not valid. Statistical (or practical) significance is sometimes overlooked by sun-weather researchers. In some of the studies listed in chapter two or within this chapter with the application of statistical significance tests is either missing or unclear, while others apply inappropriate tests based on incorrect assumptions. Table 4.1, for instance, shows that many researchers do not specify what statistical tests they have used or neglect to specify the confidence level of significance in their statistical tests. Another common problem is that researchers using superposed epoch analysis do not specify their null hypothesis, thereby making the purpose of their statistical tests unclear.

The statistical significance tests applied in this study have been selected based on two factors. The first is the non-normal distribution of the data, which might limit the accuracy parametric tests such as *t*-tests. The second is that this study is concerned with the consistency, as well as the magnitude, of the results. Two statistical tests were therefore applied to the results – sign tests and one-sample *t*-tests.

The sign test uses the chi-squared distribution to determine whether the distribution of the signs of the averages (that is, either positive or negative) differs from what can be expected due to chance. The formula for the calculation of the sign test is (*Lauroesch et al., 1996*):

$$x = \sum \frac{(O - E)^2}{E}$$

where x is the test statistic to be compared to the χ^2 distribution, O is the observed number of signs, and E is the expected number of signs. For each instance, the average values for each lag were subtracted from the *sample* median, and the sign (±) of the result was counted. In every case, E was set to $N/2$ because if the results were purely random then an equal number of positive and negative deviations would be expected (ρ = 1). Because it calculates the total number of instances for which the response index is either above or below the median the application of the sign test also affords a chance to evaluate the consistency of any observed responses to geomagnetic forcing. This is important for the practical significance of the results as well as the statistical significance.

One-sample *t*-tests were also used, despite the non-normal distribution of the daily atmospheric circulation indices. Parametric tests are still applicable to non-Gaussian distributions when the sample sizes are large (N is more than ~24) and the population distribution is not excessively non-normal (*Motulsky, 1995*). Both these conditions are generally met by the atmospheric data (recall Figures 4.1 and 4.2), so one-sample *t*-tests have been used to test the statistical significance of the averages in the superposed epoch analysis process. There are two main reasons for the use of the *t*-tests. Firstly, the use of *t*-tests is commensurate with literature for the cases that consider statistical significance. Secondly, the *t*-test uses the mean of the sample data, while the sign tests use the median. The mean is more important than the median for the superposed epoch analysis technique, which relies solely on the averaging of the data.

The statistical and practical significance of the results was also tested using randomisation. This was done in two ways. Firstly, the temporal extent of the superposed epoch analyses was extended beyond the typical interval of -5 to +10 days lag, which is standard in the literature, to -25 to +35 days lag. A possible solar influence can be expected anywhere from -5 days lag onwards[47]. There is no plausible connection between solar activity and atmospheric circulation at negative lags beyond -5 days.

[47] Recall from section 2.3.1 that many solar-weather researchers describe a 'solar-flare effect' that can precede the key date by as much as four days.

Therefore, the validity of the results and the success of the technique can be quickly evaluated by comparing the results from lags of negative five onward to those for the 'nonsense' period, -20 to -6 days lag. For example, results for the 'nonsense' period can be used to gauge the magnitude of random variations (that is, the influence of noise in the results) and it would be expected that any 'real' results should exceed this value. As mentioned earlier, extending the temporal aspect of the analysis to +35 days allows for solar-weather relationships that involves stratosphere-troposphere coupling.

The efficiency of the superposed epoch analyses technique was also evaluated by repeating each analysis with random key dates. A comparison of the random versus the 'real' results is presented in the following section.

4.4 Key dates – geomagnetic activity

The superposed epoch analyses key dates were derived for a variety of different geomagnetic conditions and for heightened solar flare activity. Not only were a number of AA values used to examine the influence of heightened geomagnetic activity on the atmospheric circulation of the lower atmosphere, but this study is unique in that it also tests for a possible influence under conditions of prolonged, low geomagnetic activity. Table 4.2 shows the three different geomagnetic conditions for which key dates were derived. An atmospheric response to undisturbed, or quiet, geomagnetic conditions was tested for by deriving key dates when the geomagnetic AA index was equal to or less than 10 nT for three or more consecutive days. Disturbed conditions, corresponding to magnetic storms, were examined by extracting key dates for when the AA index equalled or exceeded 60 nT. Finally, major geomagnetic storms occur when the geomagnetic activity index exceeds 90 nT, and this value was used to extract key dates for very disturbed conditions. When choosing key dates conditions were also placed on the AA values of previous days to prevent long-lasting geomagnetic storms – which can sometimes extend over a number of days – being incorporated more than once in each analysis. Table 4.2 also shows the number of key dates involved in each analysis.

Table 4.2. The number of key dates used in the superposed epoch analyses for different geomagnetic activity conditions for (*a*) the Antarctic Oscillation index and (*b*) the Arctic Oscillation index. Note the limited number of key dates for both the Antarctic and Arctic Oscillation indices when major geomagnetic storms (AA ≥ 90 nT) are used as key dates. The Antarctic Oscillation index spans 1979-1998, and the Arctic Oscillation index 1950-1998.

a. Antarctic Oscillation (abbreviated as SAM)

Geomagnetic Conditions (AA values)			N												
t_0	t_{-1}	t_{-2}	ALL	JFM	FMA	MAM	AMJ	MJJ	JJA	JAS	ASO	SON	OND	NDJ	DJF
≤10	≤10	≤10	226	52	44	65	68	87	62	52	36	44	54	59	55
≥60	≤30	≤30	88	18	21	23	23	20	19	20	24	27	27	23	19
≥90	≤30	≤30	16	4	5	3	2	2	2	4	4	8	6	5	3

b. Arctic Oscillation (abbreviated as NAM)

Geomagnetic Conditions (AA values)			N												
t_0	t_{-1}	t_{-2}	ALL	JFM	FMA	MAM	AMJ	MJJ	JJA	JAS	ASO	SON	OND	NDJ	DJF
≤10	≤10	≤10	763	169	155	195	206	227	193	174	159	170	214	222	205
≥60	≤30	≤30	235	60	58	59	59	54	49	56	64	64	60	59	63
≥90	≤30	≤30	46	12	13	12	8	10	11	16	15	16	10	8	7

As the table suggests, the seasonal nature of the possible relationship between solar activity and the lower atmosphere was examined by performing the superposed epoch analyses on three-monthly averaged subsets of the daily data. The sign tests and one-sample *t*-test that were performed on the results use the median and mean, respectively, of the entire three-monthly data subset on which the analyses were performed. So, for example, the averages resulting from the superposed epoch analyses of JFM averaged data are compared to the median of that entire data subset in the sign test and the mean in the one-sample *t*-test. The null hypothesis, therefore, in each of the tests is that the mean values derived using the superposed epoch analysis are no different to the mean (or the median) of the entire data set from which those values were extracted.

From Table 4.2, it can be seen that there is a trade-off between increasing the geomagnetic storm conditions and the number of key dates. For the SAM especially, which only extends from 1979 onwards in the daily data, there are so few major geomagnetic disturbance events that the analyses are meaningless. This is discussed in more detail later within this chapter.

4.5 Key dates – solar flares

Table 2.5, in chapter two, has indicated that many solar-weather researchers note an atmospheric response to solar activity a number of days before the key date. This is generally attributed to the solar flares that sometimes precede geomagnetic storms. In this chapter, however, the possible link between solar flares and atmospheric circulation is not taken for granted. Therefore, the daily atmospheric circulation indices are examined for a solar flare response, separate to the geomagnetic response.

The solar flare index used in this chapter is not provided with a quantitative measure by its providers. An arbitrary solar flare index value of 20+ was therefore chosen for the determination of key dates. This value incorporates the top 10% of solar flare index values. The number of keys dates derived when using this threshold, for both the entire annual data and the three-monthly averages, is shown in Table 4.3. The table shows that solar flare events are much more common than geomagnetic events. The *N* values generally exceed 70 for the three-monthly subsets, and are above 300 for both the SAM and NAM annual data.

Table 4.3. The number of key dates used in the superposed epoch analyses for increased solar flare activity for the Antarctic and Arctic Oscillation indices.

	N												
Index	ALL	JFM	FMA	MAM	AMJ	MJJ	JJA	JAS	ASO	SON	OND	NDJ	DJF
SAM	302	80	81	77	71	74	74	80	80	75	71	67	76
NAM	333	94	95	87	78	79	77	87	86	81	74	73	88

4.6 Results

4.6.1 Geomagnetic Activity

Figure 4.3 shows the results of the superposed epoch analysis using data for the entire year, for the three different geomagnetic conditions described previously. For these results, the threshold for statistical significance has been set at $\rho = 0.10$. Averages that are statistically significant at this level, when tested using a one-sample *t*-test, are indicated in Figure 4.3 by solid circles. The outcome of the statistical significance tests is usually similar when evaluated using sign tests, and in both cases is misleading. An interpretation of Figure 4.3, and other figures presented in this section, will explain how the superposed epoch analysis results show no indication of a link between geomagnetic activity and atmospheric circulation at the daily timescale, and that the technique itself is inappropriate.

All months

The response of the annular modes to major geomagnetic activity is shown in Figures 4.3a and 4.3b respectively. In both cases, the results show no indication of a solar-weather relationship. In the results for the NAM index, which is based on a sample size of 46 (the index spans 1950 to 1998), statistically significant variations occur between -14 and -7 days lag. This is well before any of the possible solar precursors to geomagnetic activity that may influence climate, such as solar UV changes or solar flares. These variations are definitely not related to geomagnetic activity, and are purely random.

The limited span of the daily SAM index (1979 to 1998) encompasses only 16 key dates corresponding to major geomagnetic storms. Statistically significant variations only occur at +24 and +27 days lag, and large, statistically insignificant variations close to the key date do not exceed obviously random variations at +30 to +35 days lag in magnitude. The overall impression is that the results are completely due to noise.

The results for magnetic storm conditions ($AA \geq 60$) are also indifferent, as Figures 4.3c and 4.3d show. The increased number of key dates (235 for the SAM, 88 for the NAM) has reduced the influence of noise on the results. Statistically significant variations occur at lags of +13, +14 and +19 days in the NAM data. The magnitude of the variations does not exceed that of the random variations found at extreme lags. Similarly, there are no large variations in the results for the SAM that can be associated with geomagnetic data.

Figures 4.3e and 4.3f show the response of the atmospheric circulation indices to prolonged periods of low geomagnetic activity. The large number of key dates used in each analysis has greatly reduced the impact of random variations on the results (which is the entire purpose of superposed epoch analyses) – note the generally subdued nature of the averages shown in these figures. Although there are some averages that are statistically significant, overall the variations in both these oscillation are limited in magnitude. Once again, there is no indication that atmospheric circulation responds to geomagnetic variations at the daily timescale.

Seasonal

The results presented so far have been based on all the available data. Chapter three has shown that, at decadal and interannual timescales, the relationship between geomagnetic activity and atmospheric circulation has a strong seasonal and temporal signal. It is reasonable to assume that a similar pattern may be evident at the daily timescale.

Figure 4.4 shows the response of the SAM to major geomagnetic disturbances (AA $\geq$ 90 nT) for the three-monthly subsets of the data. Note firstly that the number of averages used in each analysis (shown in the bottom right corner of each graph) is extremely low. Accordingly, the results are dominated by noise and cannot be used to either confirm or deny a relationship. The SAM response to geomagnetic disturbances (AA $\geq$ 60 nT), shown in Figure 4.5, is much more subdued. Note also that the scale of the y-axis differs between Figures 4.4 and 4.5. Once again, however, large deviations occur at a variety of lags, some of which extend well beyond the range of a possible solar influence. This indicates that the superposed epoch analysis technique has failed to overcome the noise in the data and furthermore that it is unlikely that geomagnetic activity influences the SAM at daily timescales.

One notable exception is the trough in the averages for the JFM data, which extends from -1 to +6 days lag. The variations at +1 and +2 days lag are statistically different to the overall JFM mean (ρ = 0.085 and 0.096 respectively). This result suggests that atmospheric circulation in the southern hemisphere responds immediately to geomagnetic disturbances, and that this response can span a number of days. Given the failings of the technique in general, however, it is not possible to view this result as anything but suggestive. It is in no way proof of a relationship at this timescale.

The response of the SAM to prolonged periods of low geomagnetic activity is shown in Figure 4.6. Statistically significant results are abundant, but again many of them occur at lags that are outside of the interval corresponding to a possible solar influence. This indicates that despite a moderate number of key dates (N ranges from 36 to 87) the technique has failed to overcome the noise in the data.

The results for the NAM (Figures 4.7, 4.8, and 4.9) are similarly limited by small N values and statistically significant variations occurring at improbable lags. Overall, there is no indication that atmospheric circulation responds to geomagnetic activity at the daily timescale. Further evidence that there is no relationship at this timescale is the fact that there are no similarities between the results for NAM and SAM indices at any lag.

Restricting the analyses to the most favourable conditions for the NAM does not yield significant results either. The most favourable conditions are those determined from chapter three for the annual data – a temporal restriction of 1965 onwards, a seasonal restriction of JFM for the three-monthly averages, and the QBO east phase. The results, which were calculated for key dates with AA $\geq$ 60 nT, are shown in Figure 4.10 and once again do not support a link between geomagnetic activity and atmospheric circulation. It must be noted, however, that the number of observations in each average is only eight, so the results are severely limited by noise.

4.6.2 Solar Flares

The superposed epoch analyses performed using solar flare key dates show the same limitations as the results for geomagnetic activity. Despite a larger N, the process has not overcome the noise in the atmospheric circulation indices and there are large significant and insignificant variations for the both NAM and SAM at a variety of lags. The results for all the available data are shown in Figures 4.11a and 4.11b, while the results for the three-monthly subsets are shown in Figures 4.12 and 4.13. Once again, there is no indication of a link between solar flare activity and changes in atmospheric circulation.

The conclusion that the results shown in Figures 4.3 to 4.13 are solely due to noise is supported by the comparison of the those results to results derived using random key dates. For each annual dataset or seasonal subset a second analysis was performed using randomly selected key dates (not shown). In each case, the number of random key dates is the same as the number of actual key dates. Figure 4.14 gives an example of the random results and shows that the 'real' results do not differ, in magnitude, to those that are purely noise.

4.7 Comparison to the literature

Although these results do not confirm a link between solar variability and atmospheric circulation at the daily timescale they have provided some important insights into the superposed epoch analyses technique and raised some pressing questions:

1. Can anything be deduced about the relationship based on these results?

2. It is evident that the superposed epoch analyses technique struggles to overcome the noise inherent in atmospheric data and that the statistical significance tests, when applied to the noisy data, can be misleading. Two questions are of interest – how many key dates are required for this process to work despite the noise in the data and what is the statistical power (β) of the *t*-tests?

3. Given the failings of the superposed epoch analyses technique, is there a way to improve its application or are there alternative techniques for dealing with daily data?

4. Finally, why has this technique performed so well for so many other researchers, yet in this instance has failed to confirm a relationship that is evident at annual timescales? This question is particularly important, because nearly all solar-weather studies use this technique.

These questions are addressed here in turn.

4.7.1 Can anything be deduced about daily links?

Solar-climate researchers rarely extend their analyses of annual relationships to incorporate daily relationships, and vice versa. This is despite the fact that an understanding of how solar-climate relationships operate on various timescales would not only provide valuable insights into the processes involved, but the results at both timescales can serve to validate each other. It is not unreasonable to assume, as *Schuurmans (1991)* did, that a long-term solar-climate relationship is an accumulation of individual solar-weather events. In fact, the relationship outlined in chapter three between geomagnetic activity and atmospheric circulation provided the *a priori* reasoning for the superposed epoch analyses performed here.

Surprisingly, the results of this chapter have not provided any elucidation about the relationship described in chapter three, and the only possible deduction is that geomagnetic activity does not impact upon atmospheric circulation, represented by the annular modes or the Antarctic and Arctic Oscillation indices, at the daily timescale. *Schlegel et al. (2001)* encountered a similar situation; the possible link between solar activity and lightning frequency, evident at the annual level, could not be detected at the daily timescale using superposed epoch analysis. They suggested that the relationship "…needs some temporal integration…" (page 1709) before it can be detected. Similarly, the influence of geomagnetic on atmospheric circulation may not be detectable at the daily level due to the influence of meteorological noise. *Engfer and Tinsley (1999)* also find that the amount of noise in atmospheric electricity data hindered the successful application of the superposed epoch analysis technique.

The failure of the superposed epoch analyses does not, however, compromise the results of chapter three. There are many reasons why a relationship evident at the annual and decadal levels might not be reproducible in daily data. The magnitude of the atmospheric response to a single solar event may be subtle and too small to overcome atmospheric noise, but when averaged over a month or year the difference may become noticeable. Alternatively, the impact of daily events may be cumulative, so that a single event does not result in a large, noticeable change, but when added to subsequent events the result is a detectable change in the atmospheric state. Such a phenomenon could be achieved, for example, by the modification of planetary wave propagation patterns. This assumption is supported by the e-folding timescales of both the NAO and the SAM. *Feldstein (2000)* reports an e-folding timescale of 9.5 days for the NAO index, while the e-folding timescale of the SAM is approximately 10 days (*Hartmann and Lo, 1998*).

The vague and inconsequential results could also be a due to the failing of the superposed epoch analysis technique. There is a paucity of technique available for the study of daily solar-weather relationships. Atmospheric data are generally 'noisy', while solar data report discrete events rather than a continuous phenomenon. This rules out the use of correlation techniques. Although these analyses have failed to detect a daily relationship, the following sections discuss some of the aspects of these results.

4.7.2 How many key dates are required?

Kirkland et al. (1996) report that at least 30 events are required to achieve an acceptable signal-to-noise ratio in the superposed epoch analysis of vorticity data. That number of events has been exceeded in many of the analyses in this chapter, yet no geomagnetic activity signal was detected. Table 4.1 listed details of a number of solar-weather studies that employ superposed epoch analysis. In those studies, N varies from as little as five to as much as 250. The authors of many of these studies claim to have found solar-weather relationships and, in many instances, the number of observations is quite small. The failings in this chapter cannot therefore be attributed to a small sample size.

The small sample sizes, however, combined with the level of noise in the atmospheric data limit the power of the statistical tests performed in this chapter. The statistical power of a test is the probability of successfully rejecting the null hypothesis when it is false and depends on three factors: sample size, effect size, and significance level (α) (*Hallahan and Rosenthal, 1996*). When determining power in association with the mean, as is the case with superposed epoch analyses results, the standard deviation of the data is also important. Figure 4.15 shows the power[48] of the statistical tests applied to the one-sample means used in the superposed epoch analysis procedure in this chapter. For the calculation of power, the standard deviation has been averaged across all lags from -25 to +35 days. Figure 4.15a shows that for the superposed epoch analysis for the SAM index using major geomagnetic storms as key dates, the small sample size limits the power of the one-sample *t*-test to less than 75% when the mean difference is ±0.5 or less. Figure 4.3b indicates, however, that the mean differences in the results for the SAM index do not exceed ±0.25 at any time. The power of the one-sample *t*-test in this instance is therefore only ~25%.

Conversely, mean differences in the NAM index for major geomagnetic storm conditions reach as high as -0.45, and with that magnitude the power of the associated statistical tests is close to 100% (Figure 4.15b). The SAM index mean differences for moderate geomagnetic activity generally do not exceed ±0.1 and therefore offer statistical power of no more than 25%. Mean differences in the NAM for moderate geomagnetic disturbances are of the same magnitude, but the large sample size allows statistical power of ~50%. Similarly, for both the SAM and NAM superposed epoch analyses under quiet geomagnetic conditions the large number of events allows moderate power; ~50% for the SAM and ~75% for the NAM.

It therefore seems that the number of events used in the majority of the analyses in this chapter are enough for the detection of a solar signal. The lack of such a signal in the data cannot be attributed to small sample sizes, though the inconsistent and misleading results of the statistical tests are, in part, a function of sample size.

4.7.3 Better techniques?

Lam and Samson (1994) propose that a method similar to principal component analysis serves as a better tool for superposed epoch analyses than simple averaging. Their

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[48] The power of statistical test can be estimated, based on the sample size, effect size, and significance level (*Hallahan and Rosenthal, 1996*) using published tables, or in this chapter, commercial software packages, which also incorporate the standard deviation.

method is described in *Samson and Yeung (1986)*. *Lam and Samson (1994)* argue that extreme values may mask the common structure in the averages and demonstrate the benefits of the use of principal components instead of averaging when studying the time delay between solar events and geomagnetic storms. Indeed, an examination of their Figures 1 and 2 (*Lam and Samson, 1994* page 110) clearly demonstrates that the principal-components derived results are much superior. So why has this technique not become the standard in solar-weather studies?

The main reason is that such an approach is not appropriate for exploratory analyses like those of this chapter. Some notion of the expected results is required because the principal component analyses cannot be applied to such a large lag interval as that used here. The problem is that the principal component analysis process will extract components from any data, even random data, and it is difficult to tell which variations are real. *Lam and Samson (1994)* suggest that 'real' results occur when there is a single principal component that stands out in terms of the percent of variance it can explain, but as the following paragraph indicates, this criterion was found to be inadequate.

The principal component superposed epoch analysis technique was performed for the SAM and NAM indices using key dates corresponding to geomagnetic storm conditions (AA $\geq$ 60 nT). The use of principal components, rather than averages, has not improved the results. A comparison of the principal component derived results for real and random variations (Figures C1 and C2 and Appendix C) shows that the real results are very similar to those derived using random key data. Furthermore, the leading principal components extracted for the random SAM and NAM data have relative large weightings, 23.6% and 37.3% respectively, when the interval under consideration is -5 to +10 days lag. This means that Lam and Samson's suggestion that the significance of the results can be based on the weighting the leading component is not applicable to solar-weather studies.

Therefore, while the use of principal component analysis in the superposed epoch analysis process improves the results for a known relationship it suffers from the same problems as the simple averaging method for exploratory analyses. Namely, it can produce 'real' looking results from purely random data and the statistical significance of the results is hard to determine objectively. When compared to random data, as in Figures C1 and C2, the principal components derived superposed epoch analysis technique becomes a useful tool for verifying the validity of results. The results have confirmed that there is no geomagnetic activity signal in daily variations of the annular modes.

Elsner and Kavlakov (2001) use a different method to compare hurricane intensity to geomagnetic variations. They simply averaged the 10 days of geomagnetic Kp index values that preceded each hurricane event, and then compared box-plots of these means for varying levels of hurricane intensity. Their results (shown in Figure 4.16) allowed them to conclude that maximum hurricane intensity is greater following above normal Kp index values.

This technique was applied here to the annual dataset of daily, detrended NAM index values. It was already evident, in the data preparation stage, that the technique of *Elsner and Kavlakov (2001)* is more suited to meteorological data with discrete events, like hurricanes, than it is to continuous phenomena like atmospheric circulations. Four intervals of the NAM index were chosen for comparison and are shown in Figure 4.17. Interval A includes values that are more than two standard deviations below the mean (N = 141). To avoid consecutive days being incorporated into the analyses the NAM index values for the previous day were restricted to amounts between two standard deviations below the mean and one standard deviation above it. Interval B corresponds to values that are between one and two standard deviations below the mean (N = 543) with the provision that NAM index values for the previous two days reside within one standard deviation of the mean. Intervals C (N = 574) and D (N = 158) mirror A and B, but use values that are above two and one standard deviations from the mean respectively.

The results show very little variation in the mean over the four intervals, and very little change in the distribution and number of extreme averages. Note that the extreme values (those that fall outside of the 90^{th} and 10^{th} percentiles) are shown as points outside of the box-plot. There is no relationship between the average AA index values over -10 to -1 days lag and the value of the NAM index. This confirms the results of the superposed epoch analyses presented earlier in this chapter.

The application of this technique is difficult when dealing with unitless indices like the SAM and NAM Oscillations. Furthermore, when dealing with uncertain or unknown physical processes it is difficult to know what interval to use when averaging the data. This makes the application of *Elsner and Kavlakov's (2001)* method to the data used in this chapter hazardous. Despite these difficulties, however, the results of this method and the presentation of the results as box-plots gives a greater insight into possible relationships, or lack-thereof, than the simple averages of the superposed epoch analysis technique.

All of the methods employed so far confirm that atmospheric circulation does not respond to geomagnetic activity at daily timescales. The application of these techniques to this problem, however, has highlighted limitations within the techniques themselves, regardless of the nature of the relationship being examined. Noise, in particular, is a major limitation. An alternative method, which is not as restricted by noise, is spectral analysis of daily data. *Davydova and Davydov (1996)* compared the spectra of meteorological parameters from a single station (located at approximately 43.56°N and 19.30°E) to the solar wind speed and the geomagnetic Ap index. Using data from 1979 to 1982, *Davydova and Davydov (1996)* found variations that periods of 13.5 days and 27-28 days, associated with solar activity, are evident in both the geophysical and meteorological data. Spectral analysis therefore provides a tool that can possibly overcome the noise in meteorological and geophysical data and detect relationships. It is hindered, however, by its inability to define cause-and-effect relationships and, as *Davydova and Davydov (1996)* concede, has the problem of not being able to identify phase relationships.

To overcome the problem of phase relationships, co-spectral analysis was employed in this section. In co-spectral analysis, only periodicities mutual to both time series being examined are extracted, thereby overcoming the problem of phase relationships. A relationship between either the daily NAM index or the SAM index and geomagnetic activity was not detected (Figures C3 and C4 in Appendix C). It is interesting to note, however, the presence of minor peaks in the co-spectra of the AA and NAM indices centred on periods of ~27 to 30 days and 15 days. These periods are similar to those found by *Davydova and Davydov (1996)*, but the amplitude of this signal is extremely small. Consequently, this relationship should be considered as coincidence, though it illustrates the potential of the spectral approach.

One of the obvious limitations of the spectral technique is that the data set cannot be broken up into subsets. So, for example, spectral or co-spectral analysis cannot be performed for only January, QBO east data because a relatively continuous, uninterrupted time series is required. Most importantly, it is only useful for the detection of relationships that have a relatively regular periodicity and cannot therefore replace superposed epoch analysis of solar events (which are temporally irregular), despite its shortcomings. Furthermore, the same caveats that *O'Sullivan et al. (2002)* express about the use of spectral analyses on palaeoclimate data apply to daily data. *O'Sullivan et al. (2002)* indicate that spectral analyses, when performed on the same dataset by different researchers, can yield 'completely different' results based on a number of factors including the length and possible non-stationarity of the dataset, any smoothing or filtering of the data, and the spectral analysis technique employed.

4.7.4 Why has it worked well for others?

Very few users of superposed epoch analyses concede that noise has compromised their results. *Engfer and Tinsley (1999)* are one exception; they examined the atmospheric electricity response to Forbush decrease events and geomagnetic activity, and found that their results are typically non-significant. They attributed this to the high level of noise in their data; typical diurnal variations in air-earth current density ranged from 30-40%, while the observed response to Forbush decrease events was only 4% (*Engfer and Tinsley, 1999*). It is interesting to note that they used a very wide lag interval in their analyses (from -20 to +40 days, see Table 4.1). *Stening (1994)* also used a wide interval (-20 to +20 days) and found that the majority of their results were not statistically significant.

It can be argued that the superposed epoch analysis technique has appeared to work well in many published studies because due attention has not been given to the statistical significance and the validity of the results, and because of the narrow intervals employed in the superposed epoch analyses. In much of the literature, researchers are putting undue emphasis on what are most likely random fluctuations. For example, Figure 4.18 shows the superposed epoch analyses results derived earlier for the JFM SAM response to major geomagnetic disturbances (AA $\geq$ 60 nT). In this case, however, the lag interval has been restricted to -5 to +10 days, which is typical of the intervals used in the literature. By restricting the interval in this manner these results, which previously did not support a solar-weather link, now appear to provide strong evidence to the contrary. It shows that the SAM index drops from normal values at roughly -2 days lag, down to statistically significant minima at zero and +1 days lag, and then returns to 'normal' values at +7 days lag.

By using such a narrow interval, it is not evident that deviations of this magnitude occur at many other lags and that statistically significant results can occur outside of this interval. It is highly likely, therefore, that the use of narrow intervals, small sample sizes, and questionable statistical tests, as outlined in Table 4.1, has mislead some researchers into accepting superposed epoch analysis results that are probably no more than just noise.

4.8 Conclusions

The superposed epoch analysis technique is limited in its ability to detect relationships within noisy data. These limitations include the unreliability of statistical significance tests, the power to the tests, and the inability of the technique to overcome random fluctuations in the data. This is also true for other techniques, such as a principal components based superposed epoch analysis, which also fail to overcome noise in the data. Through the scrutiny of these results and the results of other researchers it seems than many studies fail to fully acknowledge the limitations of this technique and put too much emphasis on random fluctuations.

It is not possible to recover a geomagnetic activity signature in daily indices of atmospheric circulation, despite the *a priori* expectation of such a signal based on the results of chapter three. It is likely that as well as being overwhelmed by noise the geomagnetic activity impact on the atmospheric circulation of the lower atmosphere occurs through an accumulation of subtle events that cannot be detected on an individual basis. Accordingly, this chapter has provided little insight into the temporal aspects of possible mechanisms, except that there is no clear evidence for strong mechanisms operating at lags less than 35 days.

5 Mechanisms

5.1 Introduction

The single most pressing problem in the field of solar-climate relationships is the lack of a proven mechanism linking solar variability to the climate of the lower atmosphere. In discussing the apparent relationship between solar-cycle length and surface temperatures, *Lassen and Friis-Christiansen (1995)* suggested that without a physical mechanism statistical methods alone are no longer enough to obtain new results. Their sentiments are also relevant to the entire field of solar-climate relationships. After 200 years of suggestive relationships, there is little advancement to be made by presenting statistical evidence of yet another relationship, without supporting it to some degree with a proven mechanism.

Chapter three has described a 'cause and effect' relationship between solar variability (the cause) and changes in atmospheric circulation (the effect). There is a large void between the two, however, where an appropriate solar-climate mechanism is required. The fact that there is, as yet, no proven physical mechanism that can explain solar-climate relationships is often mentioned by solar-climate critics (*Dessler, 1975*). This lack of a mechanism is a serious problem not only because it brings the validity of the entire field into question, but also because without a proper understanding of the physical processes involved it is difficult to model or predict solar-climate relationships.

There are a number of reasons why this aspect of solar-climate research is sometimes neglected and why researchers prefer to speculate about, rather than evaluate, possible mechanisms. Firstly, solar-terrestrial interactions are often complex and rely on many fields of study including astronomy, solar physics, aeronomy, and atmospheric science. It is therefore very difficult for a single researcher to be familiar with all of the concepts associated with the potential mechanisms. This sentiment is also found in *Reid (1999)*, who states that the mastery of all the fields necessary for the study of solar-climate relationships is "…clearly impossible for a single individual" (page 13). Secondly, there is a limited amount of data available to test these mechanisms. Solar data, though abundant, are generally only available for recent decades. Data on the earth's upper atmosphere are very scarce and derived largely from models (see for instance, *Fuller-Rowell et al., 1994* and *Fuller-Rowell et al., 1997*). Similarly, there is a lack of long records for a number of pertinent atmospheric parameters such as atmospheric electricity and ozone, and geophysical phenomena such as energetic electron precipitation. Furthermore, solar-climate relationships are often contentious and commonly face scepticism from parts of the climate community, so researchers may be unwilling to devote time on researching mechanisms for relationships that are still debatable. Finally, and perhaps most importantly, the development of appropriate mechanisms is hindered by the fact that most solar-climate relationships are poorly understood. While many solar-climate relationships are well described statistically, they are often not well defined in terms of spatial or temporal patterns.

This chapter therefore uses the results of chapter three, which examined various aspects of the relationship between geomagnetic activity and atmospheric circulation, to explore appropriate solar-climate mechanisms. It was hoped that the results of chapter four would also provide an insight into the relationship, but partly because of the shortcomings of the superposed epoch analysis technique and the limited magnitude of the relationship it was not possible to detect a relationship at daily timescales. The description of the appropriate mechanism involves three parts – first, the mechanism must consider (and explain) the temporal, spatial, seasonal, and timescale constraints from chapter three. Second, the terrestrial component of the mechanism must be described in terms of spatial patterns and atmospheric dynamics. Finally, the solar component of the mechanism must be described, which involves determining which geophysical process associated with geomagnetic activity is most relevant to terrestrial climate.

5.2 Mechanisms – an overview

Figure 5.1 is a schema of possible solar-climate mechanisms. In this study, the term 'mechanism' is used to refer to the physical processes that link solar activity to the troposphere. Many of these mechanisms have been described in chapter two and those that prove relevant will be described in more detail as they are examined in this chapter.

Although many of the links described in Figure 5.1 are generally accepted, such as the influence of solar activity on atmospheric ionisation or the thermospheric changes associated with solar variability, many of the other steps are unproven. Systematically examining each possible link is beyond the scope of this project. To simplify this process this chapter begins at the bottom of the flowchart shown in Figure 5.1 and works upward, examining only steps that are directly pertinent to the relationship described thus far.

At this stage, therefore, there are only two certainties. The first is that solar variability influences atmospheric circulation, as represented by the Southern and Northern Annular Modes; this was demonstrated in chapter three. The second is that changes in those modes influence climate, as described in chapter three and throughout the literature. The first question that must be addressed relates to the source of the atmospheric circulation variations – are they derived from within the troposphere, due to radiative changes, or sourced from the stratosphere through planetary wave interaction and the propagation of zonal wind anomalies?

Tinsley et al. (1989) and *Tinsley and Deen (1991)*, for instance, have suggested that changes in tropospheric thermodynamics, resulting from the electrofreezing process described in chapter two, may result in changes to tropospheric circulation. According to *Tinsley (1996a)*, changes in cyclogenesis alter meridional circulation, influencing planetary wave amplitude. Conversely, the emerging view is that changes in stratospheric dynamics also influence tropospheric circulation. Numerous studies (*Balachandran et al., 1999; Perlwitz et al., 2000; Shindell et al., 1999a, b, 2001a, b*) have unequivocally demonstrated that a change in the meridional temperature gradient of the lower stratosphere will lead to changes in tropospheric circulation. For example, *Shindell et al. (2001a)* revealed, using general circulation models, that either natural or anthropogenically derived changes in stratospheric circulation alter wind shear, which in-turn influences the propagation of planetary waves out of the troposphere. This mechanism is supported by numerous studies that demonstrate the downward propagation of the Arctic Oscillation and zonal wind anomalies from the stratosphere (or mesosphere) to the troposphere (*Baldwin et al., 1994; Baldwin and Dunkerton, 1999, 2001; Christiansen, 2001, 2002; Hartley et al., 1998; Kodera et al., 2000; Kodera and Yamazaki, 1994; Kodera and Chiba, 1995*).

It is therefore clear that, at least in the northern hemisphere, the stratosphere and troposphere are "...dynamically linked by wave-mean flow interaction" (*Perlwitz et al., 2000*; page 6916) during the cold season. This chapter will test whether this coupling is utilised by geomagnetic activity in the forcing of tropospheric circulation. It is interesting to note that some researchers have already suggested that such a mechanism may link solar activity induced changes in the stratosphere to the troposphere, though these suggestions have been made only for solar cycle changes and not specifically for geomagnetic activity variations. *Haigh (1996)* ran a general circulation model, in perpetual January mode, under solar minimum and maximum conditions and incorporated both solar irradiance and ozone changes into the model runs. The resulting link between solar activity, the stratosphere, and the troposphere differs somewhat from those described above. *Haigh (1996)* found that increased stratospheric temperature, in part due to changes in ozone, influenced the strong summer easterlies in the southern stratosphere, which subsequently penetrate into the upper troposphere and alter circulation. Despite its differences to other stratosphere-troposphere paradigms, the 'Haigh' mechanism represents one possible way in which geomagnetic activity may impact upon the troposphere.

Shindell et al. (2001b) modelled the solar irradiance changes associated with the Maunder minimum and found that although global average temperature changes were minimal, the model produced strong regional temperature changes. They attributed the large changes, observed during winter in response to a shift in the NAM and NAO indices, to the impact of solar irradiance variations on the tropopause latitudinal temperature gradient. The reduction of the tropopause latitudinal temperature gradient causes a decrease in zonal wind speed at ~40°N, decreasing the equator-ward deflection of planetary waves. *Shindell et al. (2001b)* also note that although this sequence of events was observed when ozone is removed from the model, the amplitude of the changes is greater when ozone is included. The results of *Shindell et al. (2001b)*, and their conclusion that "...relatively small solar forcing may play a significant role in century-scale NH winter climate change." (page 2151), do not concur with the results of chapter three for decadal or interannual timescales. Chapter three demonstrated that solar-cycle changes, in the form of sunspot variations, are not correlated to the Arctic or North Atlantic Oscillations. It seems, therefore, that while long-term solar irradiance changes may have a large enough magnitude to influence atmospheric circulation, the relatively minor changes associated with the 11-year solar cycle do not impact significantly on tropospheric circulation.

It has not, however, been demonstrated how or if geomagnetic activity influences the stratosphere, or whether such a link would be relevant to the troposphere. The first analyses in this chapter, therefore, examine the spatial signature of geomagnetic activity on the zonal wind and temperature fields of the troposphere and lower stratosphere. Each subsequent analysis is a sequential step designed for the deduction of the most appropriate mechanism. The first consideration, however, is the constraints that the temporal, seasonal, and spatial results of chapter three place upon possible mechanisms.

5.2.1 Constraints from chapter three

The appropriate solar-climate mechanism must be able to explain the various aspect of the geomagnetic activity-atmospheric circulation relationship outlined in chapter three. These are discussed, in turn, in this section, starting with the most perplexing of the findings – the transient nature of the correlations.

a. Temporal pattern

Chapter three has revealed that strong correlations between geomagnetic activity and atmospheric circulation occur only after ~1960. Some similarity between indices of atmospheric circulation and geomagnetic activity is evident before this time, but for both decadal and interannual variations the highest correlations occur when the analyses are restricted to 1965 onwards. This is true for both the Arctic and Antarctic oscillations.

Even though it is not uncommon for climate researchers to find that correlations are transient, the temporal inconsistency of the correlations tests the credibility of the results. *Hilmer and Jung (2000)*, for instance, found that the North Atlantic Oscillation correlated to winter Arctic sea-ice export through the Fram Strait only from 1978 onwards. No relationship is evident between 1958 and 1977. Similarly, *Kodera et al. (1999)* reported that the NAO index is correlated to the polar night jet index only after the early 1970s. Nevertheless, correlations that change sign or magnitude with time are sometimes thought to be false, and this is especially true in the already contentious field of solar-climate relationships (see *Pittock, 1983*). The transient nature of the correlations in chapter three therefore needs urgent explanation. Despite being a problem for the credibility of the relationship, the temporal pattern also acts as a useful criterion for evaluating possible mechanisms because the appropriate mechanism must exhibit a similar temporal pattern.

In this study the use of sliding correlations and cumulative sums and the separation of the data into decadal and interannual variations has allowed the temporal aspect of the correlation to be determined more reliably and objectively than *Bucha and Bucha's (1998)* methods. Accordingly, a different temporal pattern to that of Bucha and Bucha is reported in chapter three, which found no evidence for a period of negative correlations. In their study, *Bucha and Bucha (1998)* note a reversal in the sign of the correlations in 1945, from negative to positive, and strong correlations from 1970 onwards.

Their explanation for the reversal of the correlation they observed between the winter NAO and annual AA index has been described in section 2.3.2. It is based on a non-linear response, to geomagnetic forcing, of the configuration of the atmospheric pressure systems (the Icelandic low and Azores high) that determine the state of the NAO. As such, their explanation is rather circular, since the cause can also be considered the effect. The question is, what causes the atmospheric centres-of-action to adopt the configuration that they do in response to geomagnetic activity? The fact that a similar temporal pattern is evident in the southern hemisphere for the Antarctic Oscillation further confounds their theory, which can only explain the temporal inconsistencies in the AA-NAM/NAO relationship for the North Atlantic. Furthermore, when placed in the context of the Arctic Oscillation, which is evident throughout the whole of the northern hemisphere and at great heights such as in the stratosphere (*Baldwin and Dunkerton, 1999*), their explanation for the reversal of the correlation is not feasible[49].

The answer to this problem must therefore lie elsewhere. At one stage of this study, it was considered that magnitude of AA index was important and that the relationship was only evident once solar activity passed some threshold (~ 17 nT). A similar view is expressed in *Thejll et al (submitted 2002)*. In this study, however, this explanation for the temporal pattern was discounted once it was noted that magnitude of the AA index is greater in 1940s and 1950s than it is during the 1960s, but that the decadal variations between the NAM and NAO indices are not in phase with the AA index during the 1940s and 1950s.

A much more plausible explanation is that the onset of geomagnetic forcing coincides with a change that is internal to the climate system; something that probably forms an integral part of the mechanism. Although this climatic change could take on a number of forms, it must involve a phenomenon that is intermittent. Possible examples include a pre-conditioning of the atmosphere, perhaps associated with anthropogenic changes manifested as a change in the stratospheric polar vortex or stratospheric ozone concentrations, or the introduction of an atmospheric component that is a crucial ingredient for the geomagnetic forcing of the lower atmosphere. One example that will be considered in this chapter is the possible role of stratospheric aerosols, which is an obvious candidate because it exhibits a similar temporal pattern as the correlations presented in chapter three.

Alternatively, the transient nature of the correlations in chapter three may be the result of ‘noise’. For example, puzzling and abrupt climate changes that occurred during the last ice age may have been brought on by stochastic resonance (*Rahmstorf and Alley, 2002*). Stochastic resonance is sometimes invoked to explain transient phenomena in physical sciences (see, for example, *Benzi et al., 1982*) and is the concept that a weak

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[49] This is a good example of how differences in the NAO and NAM paradigms can be important.

signal can be amplified by noise (*Gammaitoni et al., 1998*). In fact, *Ruzmaikin (1999)* and *Lawrence and Ruzmaikin (1998)* have suggested that stochastic resonance may amplify the solar forcing of climate. They consider the possibility that El Niño events and changes in the Southern Oscillation amplify the 11-year solar cycle signal in global temperatures. While the findings of *Ruzmaikin (1999)* are not directly applicable to the results of chapter three, it is possible that a similar, non-linear forcing occurs in the relationship between geomagnetic activity and atmospheric circulation.

Stochastic resonance is not evaluated in this chapter, however, mainly because it is not all to different to the idea outlined previously, that the solar-climate relationship described in chapter three is modulated by some other climatic (or solar) parameter. *McNamara and Wiesenfeld (1989)* describe the three main components of stochastic resonance – a bistable system with inputs in the form of a 'coherent signal' and 'random noise', and "…an output which is some function of the inputs and the internal dynamics of the system" (page 4854). If applied to the results of chapter three, the bistable system is the earth's atmosphere, the coherent signal is solar-terrestrial coupling in the form of geomagnetic activity, and the output is the change in atmospheric circulation. Whether the missing link is random noise that amplifies solar forcing or a deterministic aspect of the climate system, as in the stratospheric aerosol example mentioned here, the same problems remains – identifying this link with the limited data available.

b. Seasonal

Solar forcing of atmospheric circulation in both hemispheres shows a strong seasonal cycle. In the southern hemisphere, the relationship between the geomagnetic AA index and the SAM index peaks in late summer/early autumn (February to April). When examined on a monthly, rather than seasonal, level the relationship is strongest for the month of March. The relationship between atmospheric circulation and geomagnetic activity occurs earlier in the year for the northern hemisphere – January for the monthly data and winter/early spring for the three-monthly averages. The strongest link occurs during the January to March average.

The results clearly indicate that the geomagnetic forcing of the atmosphere is not strictly a winter phenomenon. As reported in chapter two, many studies of the daily relationship between geomagnetic or solar activity and the lower atmosphere report that geomagnetic activity/weather relationships are either strongest in or entirely limited to the boreal winter months. *Burns et al. (1980)* and *Stening (1994)* challenged the view that solar-climate links only occur in winter. They dealt with solar-weather effects in the southern hemisphere and found the strongest response to solar forcing in the austral summer (January and February). Although they deal with annual rather than daily relationships, the results of chapter three conclusively show that the geomagnetic influence of the lower atmosphere is not specifically a boreal winter phenomenon. The correlations between the NAM and AA indices are low for early boreal winter months and of limited magnitude for the DJF average, while high correlations for the SAM index are restricted to late summer/early autumn months.

The seasonality of the AA-NAM relationship is very suggestive of a solar-climate mechanism that involves planetary waves and the northern stratospheric polar vortex, as described previously. The relationship is restricted to January in the monthly data, a time when the northern polar vortex is strong. The JFM seasonal preference corresponds to what *Thompson et al. (2000)* term the "active season for stratospheric planetary wave-mean flow interaction…" (page 1018), when the stratosphere and troposphere are strongly coupled and the northern stratospheric polar vortex is strong (*Thompson and Wallace, 2000*). Many authors describe a link between the stratospheric polar vortex and atmospheric circulation in the north Atlantic (*Perlwitz and Graf, 1995; Perlwitz et al., 2000*). This suggests that the seasonality of the results is not random, and that geomagnetic activity influences atmospheric circulation in the northern hemisphere by forcing the stratospheric polar vortex.

This interpretation is confounded by the results of the AA-SAM correlations. The southern hemisphere month for strong planetary wave activity and stratosphere-troposphere coupling (that is, the 'active season') is November (*Thompson et al., 2000*). Although there is a conspicuous correlation between the decadal AA and SAM indices for November (r = 0.65), the correlations for this month and the corresponding seasonal average are statistically insignificant and of very limited magnitude once the smoothing of the time series has been considered. Instead, the preference of the AA-SAM correlations for the FMA seasonal average corresponds to what *Thompson and Wallace (2000)* have highlighted as the 'inactive season' in the southern annular mode (February and March), and a time when the southern stratospheric polar vortex is weak.

An alternative explanation for the seasonality is that the effect of geomagnetic activity on atmospheric circulation is unrelated to the seasons and is, instead, a global effect centred on the early part of the year. The delay in the southern hemisphere response, which occurs around March, to the northern hemisphere response that first occurs in January, could be due to the thermal inertia of the southern hemisphere oceans. If this is the case, suitable mechanisms may involve the influence of geomagnetic activity on the global electric circuit, as suggested by *Stening (1994)*, or the imbalance in solar irradiance due to orbital parameters, which is 6% greater in January than in June (*Burns et al., 1980*). At this stage, the seasonality supports the other mechanism that has already been described – that of a cloud cover/transparency change which influences the radiative balance in the troposphere. These considerations, and more, will be used to evaluate the mechanisms shown in Figure 5.1.

c. Spatial

The spatial pattern described in chapter three confirms that the influence of geomagnetic forcing, at the earth's surface, is limited to the changes associated with the northern and southern annular modes. While this is enough to indicate that planetary waves are involved in the geomagnetic forcing of atmospheric circulation, it does not provide much scope for the deduction of possible mechanisms because the spatial aspect of the relationship has only been examined in two dimensions. Therefore, the bulk of the analyses performed within this chapter involve the examination of the geomagnetic activity signature in zonal-mean zonal wind and temperature data extending from the surface to heights of roughly 30 km, which allows the spatial pattern of the relationship to be examined at heights extending into the lower stratosphere.

Furthermore, the presence of a geomagnetic activity signature in the actual atmospheric data, and not just the atmospheric circulation indices, serves to confirm or deny the relationship described in chapter three. That is, correlations between the AA index and the atmospheric circulation indices that have occurred due to chance should not be well represented in the zonal-mean zonal wind or temperature data used within this chapter. Conversely, if the relationships are real then there should be clear geomagnetic activity signatures in these data with the appropriate spatial patterns. The analyses of this chapter therefore validate the findings of chapter three, though this is not the primary purpose of the analyses presented here.

d. Lagged

The results of chapter three, specifically Figure 3.16, gave some indication that there is a delay in the atmospheric response to solar activity. This aspect of the relationship is examined further in the following sections by incorporating lag into the correlations. The lag one autocorrelation of the AA index, on a monthly timescale, is strong at times. This implies that the zonal-mean zonal wind field may exhibit a delayed response to the geomagnetic activity variations of the previous month. Alternatively, the correlation result for a particular month may be the result of the strong similarity between the geomagnetic AA indices of subsequent months. For example, the lag-one correlation results for the January zonal-mean zonal wind field may arise because the January AA index is correlated to the December AA index (r = 0.71, N = 33), and not because the December AA index has any influence on atmospheric circulation in January. Because the strength of the correlation between the lagged AA indices has the potential to greatly influence the lagged correlations performed in the following sections the magnitude of the correlation is shown here in Table 5.1. Correlations at lag may also occur if the original variations in atmospheric circulation persist for a number of months.

Table 5.1. Lagged correlations for the monthly AA index. The AA index for each month has been correlated to AA values for the previous three months, in turn. For January, the correlation coefficient of 0.71 is achieved by correlating the January AA index to the December AA index of the previous year, and so on for all the months. For some months, such as October, November, and December the similarity to the following month can be high. Moderate correlations are also evident at two and even three months lag, which can confound the interpretation of the lagged analyses.

Month	Lag_1 Correlation 1965-1997	Lag_2 Correlation 1965-1997	Lag_3 Correlation 1965-1997
January	0.71	0.53	0.51
February	0.56	0.62	0.68
March	0.36	0.67	0.44
April	0.67	0.48	0.65
May	0.62	0.50	0.57
June	0.50	0.41	0.48
July	0.62	0.26	0.43
August	0.61	0.69	0.17
September	0.56	0.58	0.38
October	0.43	0.58	0.61
November	0.75	0.42	0.66
December	0.74	0.62	0.57

e. The QBO

The QBO influence on the geomagnetic forcing of the Arctic Oscillation has not been described in the literature. The QBO modulation described in chapter three is different to that found in solar-cycle/climate relationships because the correlations are strongest for QBO east phase conditions. *Labitzke and van Loon (2000),* conversely, found that correlations were strengthened most during QBO west phase conditions, and that the relationship between the solar cycle and northern polar temperatures changed sign according to the phase of the QBO. The geomagnetic forcing of the NAM contrasts with this pattern in that correlations for the QBO west phase do not change sign and are of limited magnitude. Current explanations for the QBO signal in solar-climate relationships, which are very limited, are not automatically applicable to the relationship described in chapter three.

The strong relationship between the geomagnetic AA index and the Arctic Oscillation, which is evident only during the QBO east phase in interannual data, also provides some insight into possible mechanisms. The QBO is a stratospheric phenomenon and the reliance of geomagnetic activity-atmospheric circulation relationships in the northern hemisphere on the phase of the QBO, therefore, implicates stratospheric processes in the mechanism. Conversely, the absence of QBO modulation in the southern hemisphere relationship implies that the stratosphere may not play a direct part in the geomagnetic forcing of the Antarctic Oscillation.

To exploit the presence of the QBO in the AA-NAM relationship it is important to consider what the QBO represents in terms of stratospheric changes and how the QBO modulation of geomagnetic activity differs from QBO effects in other solar-climate relationships. Unfortunately, the role of the QBO in solar-climate relationships is not clear (*Tinsley and Heelis, 1993*) and it seems that a proper understanding of the processes coupling solar activity to the lower atmosphere is necessary before the influence of the QBO can be understood.

The atmospheric changes associated with the phase of the QBO, which may be relevant to the geomagnetic forcing of the NAM, are listed below:

1. During the early boreal winter (November and December), the amplitude of planetary wavenumber 1 is 50% greater at 60°N when the QBO winds are easterly compared to when the QBO winds are westerly (*Holton and Tan, 1980*).

2. The position of the critical surface (which is the point at which the zonal-mean zonal wind is zero) in the lower stratosphere is influenced by the phase of the equatorial QBO (*Holton and Tan, 1980*). The critical surface corresponds to the planetary wave breaking zone (*Balachandran et al., 1999*) and is situated further north during the east phase of the QBO (*Holton and Tan, 1980*). Consequently, planetary wave propagation is more poleward and extends higher during the QBO east phase (*Baldwin and Dunkerton, 1998*).

3. In January, differences in composites of northern hemisphere zonal mean zonal wind for QBO east and west phases reveal that the northern polar vortex is influenced by the QBO and exhibits a NAM like structure extending above 1 hPa (*Baldwin and Dunkerton, 1998*). This feature is lacking in the southern

hemisphere because the polar vortex is not disrupted by planetary wave activity (*Baldwin and Dunkerton, 1998*).

4. In the upper stratosphere (above 10 hPa), the QBO is positively correlated to winter (DJF) zonal-mean zonal wind at 60°N and 30°S (*Baldwin and Dunkerton, 1991*). *Kodera (1991)* also reports that the QBO is correlated to high-latitude (~60°N) mean geostrophic zonal wind in the upper stratosphere (centred on an altitude of ~40 km) during December. A similar correlation pattern, also limited to December, is noted by *Baldwin and Dunkerton (1999)* who indicate that the QBO may modulate the NAM, but that the QBO influence on the NAM is strongest in the stratosphere and limited to early winter.

There are, therefore, a number of possible ways in which the QBO can modulate the geomagnetic forcing of the NAM while not playing an important role in the forcing of the SAM, which will be considered in this chapter.

5.3 Methods

To examine the spatial pattern of the geomagnetic activity signature in atmospheric circulation further the geomagnetic AA index was correlated to monthly *NCEP/NCAR* reanalysis zonal wind data (*Kalnay et al., 1996*)[50]. The zonal wind data are available for 17 geopotential heights ranging from 1000 hPa to 10 hPa and 2.5° intervals of latitude and longitude. The data therefore cover both the northern and southern hemispheres, and extend from the surface to a height of roughly 30 km, which includes the lower half of the stratosphere. The geomagnetic AA index was also correlated to zonal-mean temperature data. The temperature data have the same characteristics as the zonal wind data, and are also from the *NCEP/NCAR* reanalysis data set.

[50] The data were obtained from the *NOAA-CIRES Climate Diagnostics Center* web site, http://www.cdc.noaa.gov/cdc/reanalysis

The correlations were calculated using data from 1965 to 1997, so there are over 40,000 observations in each monthly subset of the data. The correlations were not extended beyond 1997 because of uncertainties regarding the accuracy of zonal wind data after that time[51]. Therefore, N = 33 in all instances and a correlation coefficient of 0.35 is required for statistical significance at the 95% confidence level. The effective number of observations due to autocorrelation (N_{eff}) was not used in these analyses because of the large number of correlations involved (there are 1,241 correlations for each month), and because the aim of these analyses is not specifically to confirm the solar-climate relationship described in chapter three, but to examine its spatial pattern. Furthermore, because neither the geomagnetic nor the atmospheric data are smoothed in any way, the serial correlation in the data has not been enhanced.

The correlations were performed for each month separately. To accommodate any delays between geomagnetic activity and zonal wind the correlations were lagged by up to three months. The introduction of lag allows for the detection of mechanisms that involve downward propagation of zonal-wind anomalies, as outlined in earlier sections and chapters.

The magnitude of the zonal-mean zonal wind and temperature changes associated with extremes in geomagnetic activity was examined using the 'composites technique', employed in chapter three. In this case, the zonal-mean data for the ten years of the lowest geomagnetic AA values were averaged and compared with the ten years of highest AA index values. The average AA value for the low and high years, for each month, is shown in Table 5.2. In all cases, a paired t-test confirms that the geomagnetic index averages for the high and low years are statistically different at the 95% confidence level, indicating that the composites represent changes between extremes in geomagnetic conditions.

[51] Outlined in the 'problem list' at http://www.cdc.noaa.gov/cdc/reanalysis/problems.html

Table 5.2. Average geomagnetic AA index values for the 10 years of lowest AA values and the 10 years of highest AA values, taken from 1965 to 1997. The low and high averages are statistically different at the 95% confidence level. The years of low and high geomagnetic activity are used to form composites of zonal-mean wind, and later zonal-mean temperature, data to illustrate the magnitude of changes associated with extremes of geomagnetic activity.

AA index averages	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
LOW	16.1	17.8	17.4	16.2	15.2	14.7	14.5	16.5	19.0	18.3	16.7	15.1
HIGH	27.8	37.8	37.7	35.0	30.7	29.9	28.1	29.6	31.7	32.7	31.5	27.7

5.4 Results

5.4.1 Zonal Wind

Figure 5.2 depicts the correlation coefficients between the geomagnetic AA index and zonal-mean zonal wind for each month. The results for all months have been displayed so that features that are unique to geomagnetic/solar forcing can be distinguished amongst the patterns for months without geomagnetic forcing. Note that in each monthly plot, because the *NCEP/NCAR* data are regularly spaced and there are a large number of observations (1,241 for each month), the contours shown in Figure 5.2 are derived with a minimal amount of interpolation, and this is the case with all contour plots shown in this chapter.

The correlations for December, January, February, and March stand out from other months. In particular, January and March show areas of strong correlations that correspond to the relationship outlined in chapter three. For January, there is an area of statistically significant positive correlations between 40°N and 60°N that extends to a height of ~20 km. The positive correlations continue further up into the lower stratosphere and extend from 40°N to 90°N, but are reduced in magnitude and not statistically significant at the 95% confidence level. The maximum correlation (r = 0.71) occurs at 55°N and at a geopotential height of 925 hPa. This area of positive correlations is flanked by statistically significant negative correlations. The negative correlations, which are strongest (r = -0.57) at 32.5°N at a geopotential height of 925 hPa, occur between ~15°N and 35°N and at the north pole. The geomagnetic activity signature in the January zonal-mean zonal wind field closely resembles that of the Arctic Oscillation, shown in Figure 5.3. One notable difference is the area of negative correlations, found in the northern high latitudes below 10 km, which is evident only in the geomagnetic activity signature and not with the Arctic Oscillation index.

Figure 3.33 from chapter three revealed that, through the comparison of sea-level pressure composites for years of high and low geomagnetic activity, the surface signature of geomagnetic activity coincides with that of the Arctic and North Atlantic Oscillations. In the northern hemisphere, no changes associated with geomagnetic activity were found outside of the realm of the northern annular mode. With the exception of the negative polar correlations outlined previously, the same occurs with the January zonal-mean zonal wind correlations. There is nothing to indicate that geomagnetic activity has an influence on January atmospheric circulation beyond what was described in chapter three.

The geomagnetic activity signature in the northern hemisphere zonal-mean zonal wind data for February and March is not strongly reminiscent of the corresponding NAM signature. Based on the correlations for chapter three, which were greater when three-monthly averages instead of monthly values were used, it was anticipated that the correlations evident for January would continue through the late winter into other months during which planetary wave activity is strong and the stratosphere-troposphere are coupled. This is not the case and the results highlight the benefit of increasing the resolution of climate studies beyond seasonal averages to the use of monthly data. It is enigmatic, however, that the magnitude of the correlations evident when January only data are used is not degraded with the inclusion of February and March data, even though the NAM and AA indices for each of these months individually are poorly correlated.

In terms of possible mechanisms, the results for January and December strongly suggest that geomagnetic activity variations influence tropospheric circulation in the northern hemisphere by first influencing stratospheric conditions. The results for December show a broad region of significant positive correlations, between 50°N and ~90°N, extending from the lower stratosphere (30 km) to the approximate position of the tropopause.

Statistically insignificant correlations then continue from the tropopause to the surface. Within the statistically significant region, the highest correlation coefficient ($r = 0.47$) is found at 10 hPa and 67.5°N. *Christiansen (2002)* revealed that zonal-mean zonal wind anomalies at a geopotential height of 10 hPa and a latitude of 60°N influence the phase of the Arctic Oscillation 30 days later. The correlations shown in Figure 5.2 for December encompass this area, and suggest that zonal-mean zonal wind variations resulting from geomagnetic activity can influence the January zonal wind field. The correlation between the geomagnetic AA index and the zonal-mean zonal wind at this particular point (60°N, 10 hPa) is 0.44.

The development of zonal-mean zonal wind changes in the December stratospheric polar vortex associated with changes in the AA index is demonstrated in Figure 5.4, which shows the difference between composites of high and low geomagnetic activity conditions for all months. Increases of up to 13.4 ms^{-1} occur at the 10 hPa level of the December polar vortex and decrease in magnitude towards the troposphere. Figure D1, which shows the magnitude of the differences in the composites relative to the standard deviation, indicates that the increased geomagnetic activity strengthens zonal westerlies in the December northern high latitudes by values between 50% and 100% of the standard deviation at that location.

Composites of zonal-mean zonal wind differences for January and February also show large changes between years of high and low geomagnetic activity. These changes occur in the northern high latitudes, but for January the stratosphere-troposphere coupling allows the geomagnetic influence to extend further into the troposphere. Within the troposphere, the magnitude of the zonal-mean zonal wind differences is between 150% and 200% of the corresponding zonal-mean zonal wind standard deviation (Figure 5.4). The maximum increase (8.8 ms^{-1}) is still located in the lower stratosphere, however. Without the strong stratosphere-troposphere coupling of January, the differences in February are restricted to heights above 10 km. This indicates that the stratosphere-troposphere interaction in January, described in *Thompson et al. (2000)*, is crucial to the geomagnetic forcing of atmospheric circulation in the northern hemisphere and explains the seasonality of the northern hemisphere results in chapter three.

The large differences (up to 15.3 ms^{-1}) in the 30 km equatorial stratosphere in February, which are shown in Figure 5.4 and amount to between 50% and 100% of the standard deviation, are not supported by corresponding correlations in Figure 5.2. Similarly, although the large negative changes in the August equatorial stratosphere (up to -14.8 ms^{-1}) amount to between 50% and 100% of one standard deviation of zonal wind, the relationship is not evident in the correlations shown in Figure 5.2. These changes therefore do not suggest a geomagnetic activity signature at equatorial latitudes, despite the results shown in Figure 5.4, and can instead be attributed to the bimodal distribution of the QBO, which peaks symmetrically about the mean (*Naujokat, 1986*).

To isolate the role of the QBO in the geomagnetic forcing of the NAM, all of the correlations presented in Figure 5.2 were repeated for each phase of the QBO separately. The results for the QBO east phase are shown in Figure 5.5, while the QBO west phase results are shown in Figure 5.6. The number of observations in each figure is reduced, therefore large correlation coefficients are abundant and the 'real' spatial signature of geomagnetic activity is difficult to determine. To accommodate the reduced N values, dashed lines are used to indicate the approximate threshold for statistical significance at the 95% confidence level; the thresholds have been set to the nearest 0.05-interval of correlation coefficients.

The large improvement in correlation coefficients for January is evident in Figure 5.5. Despite the large decrease in the number of observations (from 33 to 15), the area of statistically significant correlations is larger, extending further up into the stratosphere. This is especially evident for the negative correlations between 15° and 45 °N. The greatest positive correlation (r = 0.89) occurs at the surface at 57.5°N, and the greatest negative correlation (r = 0.90) at a geopotential height of 700 hPa at 35°N. The fact that the relationship between the January AA index, Arctic Oscillation, and QBO, is evident in the spatial representation in Figure 5.5 confirms the reality of this phenomenon. The improvement in the AA-SAM correlations in June for the QBO west phase data was discounted in chapter three as coincidence. This is supported by Figure 5.6, which shows that this relationship is not evident in the zonal-mean zonal wind data. The improvement in the AA-NAM correlation in November for the QBO west phase data is also unsupported by the results shown in Figure 5.6. The spatial signature of the AA index in the QBO west November zonal-mean zonal wind data does not resemble that of the NAM signature, indicating that the correlation between the AA index and the NAM presented in chapter three is unlikely to be real. This confirms the suggestion, in section 5.2.1, that an examination of the spatial signature of the correlations can serve to confirm or deny the reality of the findings in chapter three.

For the correlations during QBO east Januaries, a similar pattern to that of the geomagnetic activity signature in the northern hemisphere is evident in the southern hemisphere, though the magnitude of the correlations is less. That is, there is a broad area of positive correlations ranging from close to the southern pole to 45°S, then negative correlations extending to 15°S. In both cases, the correlations extend into the stratosphere. In fact, the geomagnetic activity signature, for January in which the QBO index is negative, is symmetrical about the equator. The magnitude of the correlations in the southern hemisphere, however, is not enough to be manifested as a correlation between the AA index and the Antarctic Oscillation. Nevertheless, the results suggest that the winter preference for solar-climate relationships is, instead, a global preference centred on January. Correlations using lag will be used later to examine if the southern hemisphere link between the AA index and the Antarctic Oscillation, which occurs only in March, originates earlier in January.

The results so far have demonstrated that while a geomagnetic activity signature is evident in both the northern hemisphere troposphere and stratosphere during January, during December the geomagnetic influence occurs mainly in the stratosphere. The QBO influence on the January results has been described – does the QBO also play a part in the December correlations? A comparison of the December geomagnetic activity signature for QBO east and west data does not provide a clear answer, but suggests that the QBO modulation is not as pronounced during December. For QBO east data, the December geomagnetic activity signature is similar to that in the unseparated data. Namely, the positive correlations in the high-latitudes are at a maximum at 30 hPa (r = 0.52 at 65°N) and decrease towards the surface. A vaguely similar pattern is evident for the QBO west data, though the greatest correlation in the band of positive correlations (r = 0.54) occurs at a geopotential height of 150 hPa and 52.5°N and the correlations do not strengthen with height. Moreover, the magnitude of the correlations in both cases is limited and, because of the limited number of observations, it is difficult to establish if these are chance patterns or reflect the real manifestation of geomagnetic activity in zonal-mean zonal wind. Figure 5.7, therefore, shows differences between composites of the five years of highest AA values and the five years of lowest AA values, for QBO east years and QBO west years separately, and vice versa.

During December, for QBO east months (Figure 5.7a), there is a pronounced difference in zonal-mean zonal wind speed above heights of 20 km between roughly 60°N and 80 °N, corresponding with a strengthening (or positive influence) on zonal wind of up to 17.5 ms^{-1} at 30 hPa. It appears that these changes occur at heights well above the extent of the *NCAR/NCEP* reanalysis data. December changes associated with high and low geomagnetic activity, during the QBO west phase (Figure 5.7b), show a similar pattern at the northern high-latitudes, demonstrating that the QBO does not modulate (greatly) the relationship during December and at this level of the stratosphere. The magnitude of the zonal wind strengthening at high-latitudes is much less (< 10ms^{-1}), however, and a stronger influence (17 ms^{-1}) is seen in equatorial zonal wind.

The reciprocal is also evident in differences between the QBO phases for high and low geomagnetic activity. Outside of the equatorial stratosphere, there is very little difference between the QBO phases during years of high geomagnetic activity (Figure 5.7c). There are some minor differences in the high latitude stratosphere for the low AA composites (Figure 5.7d). This could be due to the limited number of years (five) used in the composites, but may also be a manifestation of the correlations between the QBO and high-latitude, upper-stratospheric zonal wind reported in *Baldwin and Dunkerton (1991, 1999)* and *Kodera (1991)*. If so, the figure reveals that this phenomenon only occurs in the absence of strong geomagnetic activity, which is a feature of the relationship that has not been described in the literature.

Whereas the magnitude of changes in the composites for the December data associated with the QBO are limited, the results for January clearly show that geomagnetic forcing and the QBO interact to produce different zonal-wind patterns under different circumstances. The January QBO east differences (Figure 5.7e) exhibit the familiar pattern, evident in the geomagnetic AA index signature in zonal-mean zonal wind, which resembles the NAM and extends from the stratosphere to the troposphere. For the QBO west data, however, the largest differences occur at the equatorial stratosphere, indicating either that the geomagnetic influence occurs at the equator during the QBO west years (Figure 5.7f), rather than near the pole during the QBO east periods, or that it is a chance result attributable to the limited data set. Changes in zonal-mean zonal wind associated with geomagnetic activity during the QBO west years are negligible outside of the equatorial stratosphere. The QBO influence on high-latitude zonal wind during low geomagnetic activity is again evident in Figure 5.7h. An examination of the role of the QBO in the geomagnetic activity forcing of the NAM will be completed when temperature changes are discussed in a later section, and the hypothesis that, at least in the northern hemisphere, the geomagnetic-circulation relationship involves stratosphere-to-troposphere propagation will be further examined using lagged zonal-mean zonal wind correlations and zonal-mean temperature correlations.

Returning to the zonal wind correlations shown in Figure 5.2, the results for the southern hemisphere do not clearly indicate which mechanism can account for the terrestrial component of the geomagnetic forcing of the SAM. For March, Figure 5.2 reveals an area of statistically significant positive correlations, between 52.5°S and 67.5°S at the surface, which extend to a height of ~20 km. The highest correlation coefficient (r = 0.54) occurs at 60°S at a geopotential height of 400 hPa. Unlike the corresponding correlations in northern hemisphere January, which increase in areal extent (but decrease in magnitude) with height, the southern hemisphere March correlations are restricted to a narrow zone in the stratosphere. There is therefore limited evidence that the geomagnetic activity signature in the southern hemisphere tropospheric circulation requires interaction with the stratospheric polar vortex. That is, there are no large-scale correlations in the lower stratosphere between geomagnetic activity and zonal-wind in either February or March. This is supported by the fact that stratosphere-to-troposphere coupling in the southern hemisphere is restricted to November (*Thompson et al., 2000*), not March. The results of chapter three and Figure 5.2 do not show any statistically significant links between geomagnetic activity and atmospheric circulation for November.

Still in March, adjacent to the positive correlations are two areas of statistically significant negative correlations. Like its northern hemisphere counterpart, the geomagnetic activity signature in the southern hemisphere circulation resembles that of the corresponding annular mode, the Antarctic Oscillation (shown in Figure 5.8), except for the negative correlations at the southern polar region. The magnitude of the changes associated with geomagnetic activity are, however, much smaller. Figure 5.4, in which the composites are shown, displays changes of up to 4.1 ms^{-1} at 60°S and 300 hPa. The variability of the southern hemisphere circulation is also much smaller, so that the changes shown in the March composites in that region exceed one standard deviation (Figure D1).

It is interesting to note a similar correlation pattern in the southern hemisphere September correlations, except for the negative correlations at the southern polar region. That is, there is a region of statistically significant positive correlations around 60°S, with an adjacent area of statistically significant negative correlations south of 50°S. This spatial pattern does not translate into a significant correlation between the September Antarctic Oscillation and geomagnetic activity, but its similarity to the SAM signature in zonal-mean zonal wind is suggestive of a relationship during this month. Correlations between the AA index and the NAM and NAO are greater when the NAO is used. This can be attributed to the sometimes non-zonal configuration of atmospheric circulation in the northern hemisphere, so that the EOF-derived NAM index may not correlate well with zonal-mean data. If the SAM index is calculated using nodal points, in a similar manner to the NAO index, then the correlation coefficient between the geomagnetic AA index and the September SAM index, from 1965-1997, is 0.46 (N_{eff} = 17), which although high is not statistically significant at the 95% confidence level[52]. For this calculation, the SAM index was derived, using the definition of *Gong and Wang (1999)*, as the difference between normalised zonal-mean sea level pressure at 40°S and 65°S,

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[52] If a November SAM index is calculated in a similar manner, the resulting correlation coefficient is only 0.07. This confirms that there is no geomagnetic forcing of the SAM via the stratosphere in the same manner as the stratospheric forcing of the NAM and that the lack of a relationship for this month described in earlier chapters is not an artefact of the derivation method of the SAM.

except that zonal-mean zonal wind values were used instead of zonal-mean sea level pressure.

The resemblance of the correlations in September to those of March may provide some clue as to which mechanism operates in the southern hemisphere. The two months, March and September, stand out for two reasons. Firstly, Figure 2.15 shows that geomagnetic activity peaks in the equinoctial months, March and September. Figures 2.14 and 2.15 specifically show that geomagnetic activity is, on average, higher and geomagnetic storms are more common for the equinoctial months. This may explain why a geomagnetic activity signature in southern hemisphere zonal-mean zonal wind is only evident during these months. Figure 5.9 argues for an alternative explanation for this seasonal pattern. The figure shows the annual cycle of total column ozone, and reveals that ozone minima occur in the high-latitude southern hemisphere during March and September. At this stage, the timing of both these phenomena to the geomagnetic activity correlations in the southern hemisphere is suggestive, but does not help to determine potential mechanisms. A possible link between geomagnetic activity and ozone concentration is examined later within this chapter.

Lagged

The results from the previous section raise the possibility that the influence of geomagnetic activity on the stratospheric polar vortex in December impacts upon atmospheric circulation in January. When compared to the unlagged results, the results of the lagged correlations shown in Figure 5.10 indicate that January atmospheric circulation correlates best to January geomagnetic activity, and not December geomagnetic activity. This argues for the propagation of stratospheric circulation anomalies to the stratosphere on timescales of much less than one month – a timescale that conflicts with published studies. *Baldwin and Dunkerton (1999)*, for example, have suggested a lag time of about three weeks for anomalies to propagate from 10 hPa level to the 1000 hPa level. This means that only geomagnetic activity variations in the first 10 days of January will be manifested in the January Arctic Oscillation index. As mentioned previously, *Christiansen (2002)* suggest a timescale of roughly 30 days, while *Kodera et al. (1990)* link the strengthening of stratospheric westerlies with tropospheric circulation in February – a lag of two months. It is clear, therefore, that although the results in this chapter accommodate some lag between geomagnetic activity changes and the Arctic Oscillation index, the overall impression is that geomagnetic activity induced stratospheric circulation changes impact upon the troposphere over a shorter timescale than the typical stratosphere-troposphere propagation rate which some publications suggest. It seems, therefore, that the December changes do not cause the January changes, but instead represent a manifestation of geomagnetic activity that is restricted to the stratosphere because stratosphere-troposphere coupling does not occur until January.

An interesting feature of the lag-one correlations in the zonal-mean zonal wind data is the result for February. February zonal-mean zonal wind is, in areas, significantly correlated to January geomagnetic activity variations in both hemispheres. In the southern hemisphere, the correlations show an alternative positive/negative pattern similar to the Antarctic Oscillation index signature. The positive correlations are centred on ~57.5°S and reach a maximum of 0.60 at a height of 400 hPa. The negative correlations are at a maximum at 42.5°S, at a geopotential height of 200 hPa. In the northern hemisphere, the broad area of positive correlations is situated further north than the corresponding unlagged correlation in January, which matches the temperature correlations and composites shown in earlier figures. The northern hemisphere February correlations are probably due to the propagation time from the stratosphere to the troposphere outlined previously and also the result of the geomagnetically-forced January NAM signature persisting into February.

Correlations at greater lag (two- and three-months lag, shown in Appendix D) do not support the results shown in Figure 3.16, which suggested that the Antarctic Oscillation index correlates consistently to January geomagnetic activity variations over many months. The geomagnetic activity signature at these larger lags bears no resemblance to the Antarctic Oscillation index signature. Overall, the introduction of lag into the correlations does not improve the strength of the relationship, and it does not reveal a mechanism for the southern hemisphere relationship.

The examination of the spatial signature of geomagnetic activity in the lagged zonal-mean zonal wind data support the conclusion that the results shown in Figure 3.16, which linked the Antarctic Oscillation to geomagnetic activity over a number of months lag, are not 'real'. The results for March at two months lag (shown in Figure D2) do not support the view that geomagnetic activity in January in the northern hemisphere leads to the March AA-NAM correlations two months later, despite the strong similarity between time series of two shown in Figure 3.29.

5.4.2 Temperature

The analysis of zonal-mean zonal temperature correlations supports the findings of the previous section, which indicate that the northern hemisphere relationship relies on stratospheric dynamics. They also indicate that a different, more complex, mechanism operates in the southern hemisphere. The correlation results for the temperature data are shown in Figure 5.11 and show statistically significant, positive correlations at the tropopause and above in October, November, December, and February over a broad range of latitudes. There are also small areas of statistically significant correlations in August and September. For October onwards, the correlations extend from the southern pole to ~60°N, which is the extent of solar irradiance in the austral summer. Whether or not these correlations are the result of solar irradiance changes will be examined later within this chapter. The most important aspect of these results is that, in December, the positive correlations are coupled with negative correlations within the polar night area (that is, the northern stratospheric polar vortex). Together, these correlations influence the meridional temperature gradient of the lower stratosphere, which many researchers (*Shindell et al., 1999a; Hartmann et al., 2000*) have indicated results in changes to tropospheric circulation and the Arctic Oscillation.

It is interesting to note that the magnitude of the temperature correlations in the lower stratosphere is less than the zonal wind correlations in the troposphere. Within the polar region of negative correlations in December, the highest correlation is -0.42, at a geopotential height of 30 hPa above the northern pole. The positive correlations do not exceed a value of 0.56. The limited magnitude of the correlations, compared to the tropospheric correlations in the zonal-mean zonal wind, indicates that the geomagnetic signature in the atmosphere is amplified by non-linear processes. This supports the conclusion, in chapter four, that the failure of the superposed epoch analyses is because geomagnetic activity changes are manifested in the troposphere as an accumulation of subtle events.

The bulk of the change in the meridional temperature gradient of the stratosphere is associated with the northern stratospheric polar vortex. Figure 5.12, which shows the differences between composites of high and low geomagnetic activity conditions, reveals that temperature changes outside of the polar vortex are of negligible magnitude. They generally do not exceed 1°C, which is not even 50% of the 1965 to 1997 standard deviation of temperature values in the corresponding area (Figure D4 in Appendix D). Even the large changes (up to 3.6°C over the pole at the 70 hPa level) observed in November in the southern hemisphere high-latitude stratosphere amount to less than 50% of the standard deviation. Conversely, changes within the northern polar vortex are as large as -5.7°C in December, which is between 50% and 100% of the standard deviation. Large changes are also evident at northern polar latitudes in January (up to -4.8°C) and February (up to -4.6°C). In both the zonal-mean temperature correlations and the temperature composites, the January correlations/differences are much lower (in height) than the corresponding December patterns.

The spatial and seasonal patterns of the temperature correlations confirm the role of the stratosphere in northern hemisphere geomagnetic/circulation coupling. They also reveal that there are generally no other significant temperature changes in any other part of the lower atmosphere. This observation is supported by the temperature composites shown in Figure 5.12. Based on the lack of a geomagnetic activity signature in temperature changes, outside of what has already been described, it is possible to rule out large-scale cloud cover or atmospheric transparency changes as agents of solar forcing on annual timescales. It also agrees with the analyses performed in chapter two, which suggest that long-term relationships between geomagnetic activity and global or hemispheric surface temperatures (see, for instance, *Cliver et al., 1998*) may not be resolved at regional levels.

The role of the QBO.

The influence of the QBO on the temperature correlations, for the pertinent months of December and January, is shown in Figure 5.13. The figure shows that correlations between geomagnetic activity and zonal-mean temperature during December are similar for both the QBO east and west phases, though the magnitude of the correlations is slightly lower for the QBO west phase. Conversely, the strong correlations evident in January for the QBO east phase are not mirrored in the data for the QBO west phase. This indicates that the occurrence of geomagnetic forcing in the stratosphere, during December, is not influenced by the QBO, and it is only the propagation of this effect from the stratosphere to the troposphere in January that relies on the QBO phase.

These results, combined with the zonal-mean zonal wind correlations presented earlier, make it possible to explain the role of the QBO in the geomagnetic activity forcing of the northern hemisphere circulation. It is observed that the QBO influence on geomagnetic correlations in zonal wind and temperature is very pronounced during January but minimal in December. For Januarys with a QBO west phase, there is practically no geomagnetic activity signature in the troposphere, in either zonal-mean zonal wind or zonal-mean temperature data. There are two likely explanations for the presence of the QBO in this relationship. In the first explanation, the geomagnetic activity influence in December contributes to the January zonal-mean zonal wind field by working with the QBO. This can be viewed as a 'top-down' influence, because it relies on the QBO correlations seen in the middle stratosphere described in the work of *Baldwin and Dunkerton (1991, 1999)* and *Kodera (1991)*. In essence, this view is the same as that of *Kodera et al. (1991)*, who suggested that the QBO signal in the solar cycle forcing of the northern stratosphere occurs because of the interaction of both the QBO and the solar cycle with planetary waves. The main difference to Kodera's hypothesis is that geomagnetic activity forces the stratosphere, and not the sunspot cycle, and that the sign of the relationship is not changed by the QBO.

The alternative (and preferred) explanation can be conceptualised as a 'bottom-up' influence, and finds more support in the results so far than the 'top-down' paradigm. In this view, the QBO east only occurrence of geomagnetic forcing involves the influence of the QBO on the critical surface, described in *Holton and Tan (1980)*. Since QBO east conditions shift the critical surface northward and allow planetary waves to propagate higher and more poleward than they would under QBO west conditions (*Baldwin and Dunkerton, 1998*), it allows the tropospheric circulation to interact more readily with the stratospheric changes associated with geomagnetic activity in December and January. By doing so, the zonal-wind anomalies in the stratosphere influence tropospheric circulation via a number of possible mechanisms, outlined in *Baldwin and Dunkerton (2001)* and *Shindell et al. (2001)*. It is important to note, however, that QBO east conditions are not required for the downward propagation of the NAM or of zonal wind anomalies, so the role of the QBO east in the relationship described here is specific to geomagnetic anomalies, perhaps because of their spatial or seasonal configuration.

5.4.3 Temporal pattern

It has not been automatically assumed that the temporal pattern exhibited by correlations between geomagnetic activity and the SAM and NAM indices (described in chapter three) also occurs for the zonal-mean zonal wind data. This section therefore tests if the strengthening of the AA-NAM and AA-SAM correlations after the early 1960s is mirrored in the zonal-mean zonal wind and temperature correlations. Furthermore, the temporal pattern of the correlations can be used to clarify the appropriate mechanisms. This is because, at some stage in the chain of events that links solar variability to atmospheric circulation, the temporal restriction outlined in chapter three is introduced into the geomagnetic-circulation relationship. To test if this temporal restriction occurs before or after the stratospheric circulation changes, correlation coefficients between monthly geomagnetic activity and zonal-mean zonal wind were also calculated for the period 1950 to 1960. The results are shown in Figure 5.14. In all instances $N = 11$, so a correlation coefficient of 0.60 is required for statistical significance at the 95% confidence level. The spatial pattern of the correlations, more so than the magnitude, is of interest here.

Accordingly, a comparison of Figure 5.14, which shows the correlations between geomagnetic activity and zonal-mean zonal wind from 1950 to 1960, to Figure 5.2 reveals that the spatial pattern in the correlations from 1965 onwards is generally not mirrored by the 1950-1960 data. When compared to the geomagnetic AA index, zonal-mean zonal wind variations show similar temporal correlation patterns to the atmospheric circulation indices. This indicates that the cause of the temporal pattern in chapter three must be located higher up in the chain-of-events that link geomagnetic activity to the troposphere. A similar investigation conducted for zonal-mean temperature data also indicates that the strengthening, or 'turning on', of geomagnetic forcing occurs in an earlier stage of the mechanism. Zonal-mean temperature correlations for 1950 to 1960, shown in Figure 5.15, do not show any similarities to the correlations for 1965 onwards, which supports the conclusion regarding the temporal pattern.

5.5 Stratospheric origins

Part of the mechanism linking geomagnetic activity to the northern hemisphere troposphere is clear. In the northern hemisphere, geomagnetic activity has a distinct signature in the December stratosphere, as evidenced by high correlations. These correlations are relatively unaffected by the phase of the QBO and are best observed as temperature changes in the stratospheric polar vortex. The cooling of the polar vortex under high geomagnetic conditions, coupled with the slight warming of the extra-polar stratosphere, changes the meridional temperature gradient of the lower stratosphere. This strengthens the zonal winds at the edge of the polar vortex and through stratosphere-troposphere coupling in January alters tropospheric circulation. This accounts for the correlation between the AA and NAM (and NAO) indices evident only in January.

A mechanism for the southern hemisphere is not as forthcoming. Correlations between geomagnetic activity and temperature reveal strong positive correlations in the lower stratosphere, but not in the troposphere. Direct radiative forcing of planetary wave amplitude or position in the southern hemisphere troposphere is not supported by the temperature correlations and this subsequently excludes cosmic-ray induced cloud cover changes as a potential forcing mechanism. Furthermore, the same stratosphere-troposphere coupling evident in the northern hemisphere is somewhat lacking in the southern hemisphere. There are correlations evident in the February stratosphere, which may be a precursor to the March geomagnetic forcing of the SAM. The modelled results of *Haigh (1996)* provide some support for a mechanism in the southern hemisphere. *Haigh (1996)* found that unlike the northern hemisphere stratosphere-troposphere coupling, changes in summer easterlies are important in the summer hemisphere. Warming, caused in the model by solar UV variations, strengthens summer stratosphere easterlies, which push the westerly jets to move poleward. The exploration of the solar component of geomagnetic activity forcing should shed more light on the problem, especially whether ozone changes can be attributed to geomagnetic activity or not.

The understanding of the mechanism derived from the analyses so far is shown in Figure 5.16, which is an updated version of Figure 5.1. The task now is to explain the origin of the stratospheric changes and the solar component of the mechanism – essentially, what influences the meridional temperature gradient of the lower stratosphere? This section also performs another important task – it considers what geomagnetic activity represents in-terms of solar-terrestrial coupling. Chapter two listed the solar-terrestrial links that are potentially parameterised by the geomagnetic AA index. These are (1) upper atmosphere temperature, dynamics, and composition changes, (2) cosmic-ray flux (galactic and solar), and (3) solar irradiance changes. Some understanding of which solar and terrestrial processes can be reliably associated with indices of geomagnetic activity, which is currently lacking in the field of solar-climate relationships, will help with evaluating mechanisms.

This section will use observational data, where possible, to evaluate possible mechanisms. Where observational data are lacking, assumptions regarding mechanisms will be based on the literature. *Laštovička (1996)* asserts that although the focus of solar-weather (and solar-climate) studies should now be the determination of a mechanism that can explain the tropospheric effects of geomagnetic activity, there is not as yet a complete enough understanding of these effects. This section will demonstrate, however, that the greatest hindrance to the pursuit of solar-climate mechanisms is a lack of observational data for a number of middle and upper atmosphere parameters, and not the incomplete understanding of how geomagnetic activity influences the troposphere. This suggestion is supported by *Haigh (2001)*, who suggests that the lack of reliable, long-term solar and meteorological data is one of the key challenges that must be addressed in the field of solar climate studies.

It has been the major premise of this thesis, however, that a greater understanding of solar-climate relationships can help with the deduction of appropriate mechanisms by providing spatial, temporal, seasonal, and other constraints. The main difference between the attempts of this chapter to identify a mechanism, compared to many published studies, is that the mechanism is being deduced for a specific relationship, described in chapter three and earlier sections of this chapter. Numerous aspects of this relationship have been explored and the aspects of the relationship revealed so far can be added to the constraints outlined earlier and used to evaluate potential mechanisms.

The further constraints derived so far include the spatial (altitudinal) and seasonal pattern of the zonal-mean zonal wind and temperature correlations, as well as the temporal pattern; the introduction of lag into the correlations does not improve the strength of the relationship, indicating that geomagnetic activity is coupled to the troposphere on timescales of less than one month.

With these constraints in mind, the possible mechanisms depicted in Figure 5.16 are evaluated. Four possible sources of the stratospheric changes are considered – three involve a direct impact of geomagnetic activity on the stratosphere and incorporate (a) radiative changes, (b) changes in ozone, (c) changes in stratospheric aerosols, while the fourth involves the indirect influence of geomagnetic activity changes in the upper atmosphere (mesosphere/thermosphere).

5.5.1 Radiative

Annual/Monthly. Chapter two mentioned the possibility that geomagnetic activity changes may be a suitable proxy for solar irradiance changes. *Cliver et al. (1998)* suggested as much when they found that changes in the decadal averages of global surface temperature are well correlated to the smoothed geomagnetic AA index. Figure 5.17, however, shows that the geomagnetic AA index is uncorrelated to total solar irradiance variations from the period 1978 to 1993. The solar irradiance data used in

Figure 5.17 are the Earth Radiation Budget (ERB) measurements (in W/m^2), from the *NASA Climatology Interdisciplinary Data Collection*[53]. The correlation coefficient between the monthly ERB data and the AA index is 0.05 (N = 171), which conclusively demonstrates that direct solar irradiance changes cannot be invoked as a mechanism in geomagnetic activity-climate relationships.

Surprisingly, the correlation coefficient between the ERB total solar irradiance data and the sunspot number is only 0.61. Although this is a relatively strong correlation, it reveals that the sunspot number, or the 10.7 cm solar flux[54], is not a perfect index of solar irradiance changes. Studies that assume that solar activity is well represented by sunspot activity and use the sunspot index of 10.7 cm flux as a proxy for irradiance, either in correlations using observational data (for example, *van Loon and Labitzke, 1999*) or models (*Kodera et al., 1991; Shindell et al., 2001a*) may be underestimating the magnitude of solar-climate relationships.

Daily. As section 2.2.3 has already suggested, there is reasonable evidence to allow the assumption that short-term changes in solar irradiance, mainly in the ultraviolet wavelength, are well represented by geomagnetic activity. This includes the research of *Troshichev and Gabis (1998)*, which associates solar ultraviolet irradiance changes with a variety of short-term solar phenomena. These events include solar proton events, Forbush decreases, and the passage of solar active regions. Each of these events can sometimes have a corresponding signature in geomagnetic activity, as outlined in chapter two. Through the application of the superposed epoch analysis technique, *Troshichev and Gabis (1998)* report increases in the *MgII* index[55] between 0.2% and 0.4%, associated with each of the three events.

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[53] http://daac.gsfc.nasa.gov/CAMPAIGN_DOCS/FTP_SITE/INT_DIS/readmes/sol_irrad.html

[54] Many authors use the 10.7 cm solar flux index instead of the sunspot number. The two series are, however, practically identical and interchangeable. From 1947 to 2000, the period for which the solar flux data are available, the correlation coefficient between the two annual indices is 0.99. The solar flux data used in this thesis were obtained from ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_RADIO/FLUX

[55] The *MgII* index is a robust proxy for solar ultraviolet irradiance at wavelengths of 150 to 400 nm (*Viereck and Puga, 1998*).

The results presented here, however, indicate that this relationship cannot be extrapolated to geomagnetic activity in general. Superposed epoch analysis was performed on the *NOAA MgII* index (version 9.1), obtained from the *NOAA Space Environment Center* web page online data section[56] (*Viereck and Puga, 1999; Viereck et al., 2001*). The data are available from November 7, 1978, and extend beyond the range of the daily AA index used in the analyses (December 31, 1998). Figure 5.18a shows the results of the superposed epoch analysis for geomagnetic storm conditions (AA $\geq$ 60 nT). The figure shows the deviations in the *MgII* index, which is unitless, as percentages of the mean of the *MgII* index from November 1978 to December 1998. The deviations show an overall positive tendency – this is not associated with geomagnetic forcing but results from the coincidence of solar maxima and the increased frequency of geomagnetic storms. In the same manner as the superposed epoch analyses conducted in chapter four, these results show the largest deviations at improbable lags – either well before the key date or a number of days after it (~20 days). Furthermore, the smallest deviation from the overall mean (0.06%) occurs at a lag of one day (*i.e.*, in close proximity to geomagnetic storm days). Overall, there is no indication that geomagnetic activity functions as a proxy for solar ultraviolet irradiance variations at the daily timescale.

This is reinforced with the results shown in Figure 5.18b, which shows the superposed epoch analysis for periods of prolonged geomagnetically quiet conditions (AA $\leq$ 10 nT for three consecutive days). The results show an overall negative tendency, once again associated with the long-term sunspot cycle and not day-to-day geomagnetic variations. Therefore, there are no statistically or practically significant deviations in solar ultraviolet radiation associated with geomagnetic activity at the daily timescale.

These revelations regarding geomagnetic activity and solar irradiance have ruled out direct radiative forcing as a potential cause for the stratospheric changes, at least on timescales less than a year. The analyses presented here, however, do not counter claims

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[56] Information from the Space Environment Center, Boulder, CO, National Oceanic and Atmospheric Administration (NOAA), US Dept. of Commerce – http://www.sel.noaa.gov/ftpdir/sbuv/NOAAMgII.dat

that long-term changes in geomagnetic activity are mirrored by changes in solar irradiance, as suggested by *Lockwood et al. (1999)* and *Beer et al. (1998)*.

5.5.2 Ozone

A tremendous amount of uncertainty and contradiction exists regarding the impact of geomagnetic and solar activity on ozone concentration and the literature on this topic presents an abundance of conflicting ideas. The uncertainties are associated not only with the quantitative aspect of the relationships (*Bazilevskaya et al., 2000*), but also the sign of the relationship (increase/decrease) and the actual solar phenomenon driving these changes.

A number of authors note, on daily timescales, a decrease in ozone in response to solar proton events (*Jackman et al., 1999; Krivolutsky, 2001)*. By simulating the influence of solar proton events in a two-dimensional chemistry and transport atmospheric model, *Jackman et al. (1999)* found that the odd nitrogen created by solar proton events in the upper atmosphere resulted in stratospheric ozone decreases because of the large-scale circulation in the stratosphere during winter. Similarly, *Krivolutsky (2001)* used model and observational data to conclude that solar proton events lead to short-term ozone decreases in mesospheric polar regions of both hemispheres. Geomagnetic activity, however, is not a strong proxy for solar proton events, so the findings of *Jackman et al. (1999)* and *Krivolutsky (2001)* cannot be interpreted as evidence for a link between geomagnetic activity and stratospheric ozone.

Other authors describe a similar decrease in ozone, once again at daily timescales, related specifically to geomagnetic variations rather than solar proton events (*Marcucci et al., 1999; Storini, 2001*). The results of *Marcucci et al. (1999)* are shown in Table 5.3. The table shows the correlation coefficient between the daily auroral electrojet index (the AE index) and ‘spring’ (August 20 to November 20) Antarctic ozone depletion within the southern stratospheric polar vortex. It shows that correlation coefficients ranging from 0.41 to 0.80 occur between these two parameters at lags between eight to 15 days. The AE index is a measure of ionospheric current flow at auroral latitudes and altitudes of roughly 100 km (*Tsurutani and Gonzalez, 1998*) and is generally only considered on hourly or daily timescales. *Ahn et al. (2000)*, however, compared annual values of the AE and AA indices and concluded, from the strong visual resemblance of the two time series, that both indices are intensified by the same mechanism. Therefore, the results of *Marcucci et al.* can be extrapolated to indicate a possible inverse relationship between geomagnetic activity (as represented by the AA index) and ozone concentration, particularly in the southern hemisphere during spring.

Table 5.3. Correlation coefficients between the AE index and Antarctic ozone depletion, from *Marcucci et al. (1999)*. Data within this table were extracted from Table 2 in *Marcucci et al.* and indicate that when auroral electrojet activity is high the ozone concentration in the spring antarctic polar vortex decreases after roughly ten days.

Year	*r*	Lag (days)
1979	0.44	10
1980	0.63	11
1981	0.56	11
1982	0.80	13
1983	0.55	10
1984	0.64	13
1985	0.44	10
1986	0.66	15
1987	0.41	9
1990	0.69	8

Storini (2001) also examined daily links between northern hemisphere total ozone concentration and the AE index, and found a strong negative correlation (r = -0.91) between indices of the two during a coronal mass ejection induced disturbance in 1982. The correlations are greatest for ozone changes in the geomagnetic middle latitudes[57], between 60°N and 75°N. A lesser correlation (r = -0.51) was found at high (75°N to 90°N) geomagnetic latitudes.

Conversely, others describe a positive relationship between ozone concentrations and solar-terrestrial phenomena associated with geomagnetic activity. The results of *Makarova and Shirochkov (2001)* are extremely vague and contradictory, but seem to suggest an inverse relationship (r = -0.7) between ozone concentration and atmospheric electricity at Vostok, in Antarctica (~78°S), during 1998. Atmospheric electricity is modulated by cosmic rays (*Tinsley, 1996a*), so there is an inverse relationship between geomagnetic activity and the vertical current in the atmosphere. This translates to a

[57] Geomagnetic latitude differs from geographic latitude. In this case, the middle geomagnetic latitudes correspond to the auroral ovals.

positive relationship between geomagnetic activity and ozone, but details of this relationship are poorly expressed in *Makarova and Shirochkov (2001)*.

The results of *Lu and Sanche (2001)* can also be interpreted as a positive relationship between geomagnetic activity and ozone concentration. They demonstrated that the annual average total ozone values between 0°S and 65°S, from 1979 to 1992, are inversely related to cosmic ray flux (Figure 5.19). They extrapolate this to indicate that winter stratospheric polar ozone is destroyed by cosmic rays, even though the changes shown in Figure 5.19 (their Figure 3) are not for polar areas. The importance of *Lu and Sanche's (2001)* results is that, although the relationship they describe is not quantified by means of correlation coefficients, it is presented using annual data and is therefore more relevant to the annual and decadal relationships presented in chapter three and section 5.4 than the daily results. Chapter four has already proven that annual results cannot automatically be extrapolated to daily timescales, and the reverse is assumed here also.

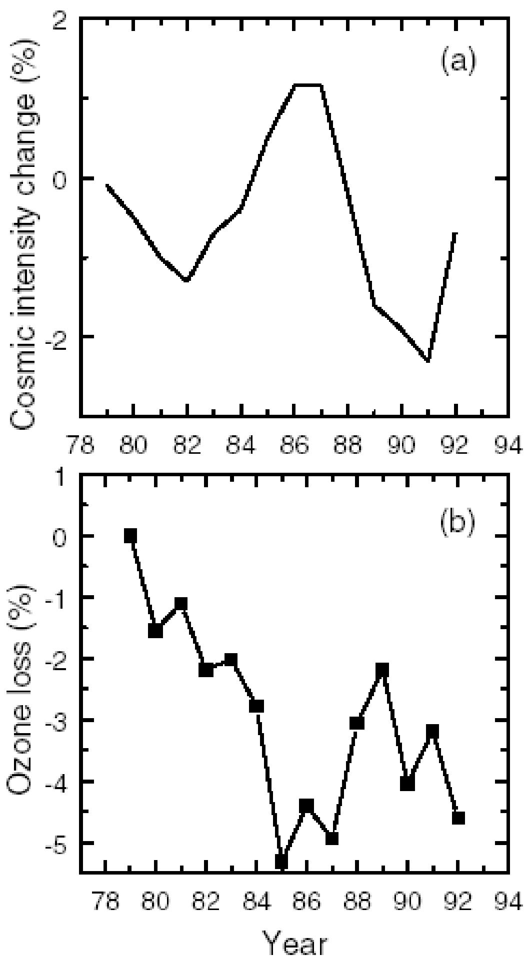

Figure 5.19. Cosmic-ray flux versus total ozone concentration, 0°-65°S, from *Lu and Sanche (2001)*. The inverse relationship between cosmic ray flux and ozone concentration means a positive relationship between geomagnetic activity and ozone.

The findings of *Krivolutsky et al. (2001, 2002)* are in direct contrast to those of *Lu and Sanche (2001)*. *Krivolutsky et al. (2001, 2002)* suggested that cosmic ray flux at 20 km is positively correlated to total ozone concentration over Russia, which implies an inverse relationship between geomagnetic activity and ozone. They also used yearly data in their regression analyses and photochemical modelling, but their results are so obscure it is difficult to interpret even the crudest aspects of this relationship.

Finally, *Laštovička (1990)* used superposed epoch analyses to demonstrate that geomagnetic activity has no influence on middle stratosphere ozone between 40°N and 60°N. However, *Laštovička (1990)* declared that it would be interesting to examine geomagnetic activity induced ozone changes at higher latitudes, which have been associated with energetic particle precipitation/penetration by other researchers. Consequently, it was *Laštovička (1996), Laštovička and Mlch (1999)*, and *Fedulina and Laštovička (2001)* who further explored the response of ozone to geomagnetic activity. *Fedulina and Laštovička (2001)* described a ‘significant’ increase in total column ozone, over Europe at 50°N, three days after Forbush decrease events and increased geomagnetic activity. They noted, however, that this relationship is spatially restricted (it does not occur at 40°N), seasonally restricted, since it only occurs during the boreal winter, and is dependent on the QBO winds being eastward. They indicate, however, that this relationship is not a direct result of a geomagnetic influence on ozone. Instead, they attribute the regional ozone changes to possible variations in planetary wave activity associated with geomagnetic activity (*Laštovička and Mlch, 1999*)

The findings of the aforementioned studies are summarised in Table 5.4. The table indicates that there is very little consensus about the role of geomagnetic activity in ozone changes, that most of the studies only consider daily timescales, and that the magnitude and sign of the response varies according to the location. Given the limitation of the literature regarding a possible geomagnetic activity signature in ozone concentrations, monthly ozone data were obtained and compared to the geomagnetic AA index. The data were also compared to the sunspot cycle to evaluate links between solar irradiance and ozone and to investigate similarities and contrasts between solar and geomagnetic forcing of the stratosphere.

Table 5.4. Findings in recent studies of solar activity impacts on ozone concentration. This table demonstrates that there is a lot of uncertainty regarding the possible influence of solar variability on ozone concentrations. Accordingly, monthly ozone data are used in the following sections to evaluate the role of geomagnetic activity in ozone changes.

Author(s)	Time-scale	Solar Phenomena	Location	Altitude	Relationship	Relationship to Geomagnetic Activity
Jackman et al. (1999)	Daily	SPE	Polar regions	Stratosphere	Negative	Unclear
Krivolutsky (2001)	Daily	SPE	Polar regions	Mesosphere	Negative	Unclear
Marcucci et al. (1999)	Daily	AE index	Southern polar vortex	Stratosphere	*r* ranges 0.41 to 0.80	Negative
Makarova and Shirochkov (2001)	Daily	Magnetopause radius	Vostok, Antarctica (~78°S)	All (total ozone)	Negative (r = -0.7)	Positive
Lu and Sanche (2001)	Annual	Cosmic Rays	0°-65°S	All (total ozone)	Negative	Positive
Storini (2001)	Daily	AE index	Auroral oval	All (total ozone)	Negative (*r* = -0.91)	Negative
Krivolutsky et al. (2001, 2002)	Annual ?	Cosmic Rays	Russia (~55°N, ~69°N)	20 km	Positive	Negative

Monthly zonal-mean total column ozone data were obtained from the *Total Ozone Mapping Spectrometer* (TOMS) web page[58]. The data are derived from three separate platforms: *Nimbus 7* (1978-1993), *Meteor 3* (1991-1994), and *Earth Probe* (1996-present) and are available for 5° latitudinal zones from 90°N to 90°S. The analyses of this section used the *Nimbus 7* data from 1978 to 1992, the *Meteor 3* data for 1993 and 1994, and the *Earth Probe* data from late 1996, 1997, and 1998.

The zonal-mean total ozone data were correlated to the geomagnetic AA index and the 10.7 cm solar flux index for each month separately. The spatial and seasonal aspects of the results are of greater interest than the magnitude of the correlations, because they might help explain the patterns in chapter three and earlier sections of this chapter. The results, however, shown in Figures 5.20 and 5.21, do not provide any explanation for earlier results. Figure 5.20 shows the correlations between the zonal-mean total column ozone and the geomagnetic AA index. The number of observations in each correlation is generally 17 or 18, though it is higher for November (20) December (19). If the effects of serial correlation are ignored, the required level for statistical significance is roughly

[58] http://toms.gsfc.nasa.gov/ozone/ozoneother.html

0.48. The level of serial correlation in the AA index varies greatly by month, so calculations of the effective number of observations yield results ranging from 10 to 17 or 18. Overall, however, the impact of serial correlation is limited and N_{eff} averages 16. This requires a correlation coefficient of 0.49 for statistical significance at the 95% confidence level – a condition that is rarely fulfilled in the results shown in Figure 5.20.

The most important aspects of the result, however, is that fact that the spatial and seasonal patterns do not match those in Figure 5.11, which shows zonal-mean temperature correlations. The strong correlations in the zonal-mean temperatures for October, November, and December, are not mirrored in the ozone results. This indicates that geomagnetic activity does not have a statistically or practically significant impact on total column ozone outside of the winter polar region. TOMS data are not available for the polar night areas, so it is not clear what effect geomagnetic activity may have on ozone concentrations during winter.

Correlations between the 10.7 cm solar flux and zonal-mean total column ozone, shown in Figure 5.21, are stronger than the corresponding correlations shown in Figure 5.20. It must be acknowledged, however, that the increased magnitude of the correlations is at least partly due to the lack of interannual variations in the solar flux index, when compared to the geomagnetic AA index (recall Figure 2.15). This not only yields higher correlations, but also results in a much lower N_{eff} for the solar flux correlations, due to the strong serial correlation in the solar flux index. The number of effective observations averages 12, requiring correlation coefficients of 0.57 for statistical significance.

Although this is sometimes exceeded by the correlations shown in Figure 5.21, the results do not show the same spatial and seasonal pattern as the zonal-temperature correlations. Even if there is a relationship between the solar irradiance variations and total column ozone, it is not the crucial step in the mechanism linking geomagnetic activity or solar variability to atmospheric circulation in the troposphere. This conclusion is supported by the results of chapter three, which revealed that neither the Antarctic nor the Arctic Oscillation indices are correlated to the sunspot number.

The solar flux correlations, however, support the view that there is a solar-cycle signal in ozone concentrations (see, for instance, *Hood 1997*), but have not evaluated the suggestion that the relationship is modulated by the QBO (*Varotsos, 1989*) since the total ozone column data were not separated according to the phase of the QBO. The most convincing feature of the results is the peak in the zonal correlations, for months such as December through to April and July through to September, which in each case occurs at ~20° latitude in the summer hemisphere. This indicates that the solar cycle influence on ozone is in part radiative, as the latitudinal peaks coincide with the area and timing of maximum irradiance. In fact, *Hood (1999)* presents strong evidence of a link between solar UV and upper stratospheric ozone, which has significant implications for solar-climate relationships at decadal timescales.

The results of monthly ozone analyses and a review of the recent literature have not described a viable geomagnetic/troposphere mechanisms involving ozone. Ozone changes in the most relevant region, the northern polar vortex, have not been evaluated due to a lack of available data. The lack of geomagnetic correlation to ozone, which is the main shortcoming that would hinder the acceptance of this mechanism, can perhaps be attributed to the use of total column, zonal-mean ozone values. The vertical and meridional integration of ozone values may mask the influence of geomagnetic activity, which might only occur at specific heights and longitudes. The results of section 5.4 indicate that if the zonal-mean temperature correlations are related to ozone then this relationship is generally restricted to the lower stratosphere/tropopause region, not the entire atmosphere (that is, the total column of ozone). *Chandra et al. (1999)* have shown that the solar signature in tropospheric ozone is out-of-phase with the solar signature in stratospheric ozone because stratospheric changes in ozone related to the solar cycle influence the UVB flux reaching the troposphere, which in turn impacts upon tropospheric ozone. Although this problem is mediated by the fact that the bulk of ozone occurs in the stratosphere (*Storini, 2001*), it may nevertheless explain why correlations between geomagnetic activity and total column ozone are negligible, while many other studies have found links between geomagnetic activity and ozone.

The findings of *Callis et al. (1998a, b, 2001)*, for instance, present strong evidence for solar-coupling via energetic electrons associated with the solar wind, nitrogen oxide in the middle atmosphere, and stratospheric ozone. The temporal aspects of this relationship (in particular, the lag between increases in electron flux and ozone depletion) make it unclear whether it is applicable to the relationships discovered within this thesis. Overall, however, the findings of Callis et al. and the other researchers listed in this section present some evidence for a geomagnetic influence on ozone. Subsequently, such a relationship could explain southern hemisphere temperature changes observed in Figure 5.11, which then influence the troposphere via the mechanism described in *Haigh (1996)*. In fact, the importance of ozone changes to the SAM is described in *Thompson and Solomon (2002)*, and it is therefore very feasible (and more credible) that geomagnetic activity influences the SAM through established, internal atmospheric processes rather than complicated alternatives. The ozone forcing described in *Thompson and Solomon (2002)* occurs via the stratospheric polar vortex, and it therefore operates differently to the Haigh mechanism that originates in the tropics. Nevertheless, both mechanisms represent potential pathways through which geomagnetic activity can influence the SAM.

This mechanism (*i.e.*, geomagnetic forcing of stratospheric circulation via ozone changes) may also explain northern hemisphere changes in the winter polar vortex, despite the lack of irradiance making ozone irrelevant. This is because of the ‘twilight effect’, associated with stratospheric aerosols and described in the following section.

5.5.3 Stratospheric Aerosols

The accumulation of stratospheric aerosols at heights between 10 and 15 km, varying with latitude, is known as the Junge layer and results from the temperature inversions and general atmospheric stability at the tropopause (*Pueschel, 1996*). Therefore, like ozone, high concentrations of aerosols also occur in locations relevant to the stratospheric changes observed in section 5.4.

One possible explanation for the temporal pattern of the correlations in chapter three can be found in Figure 5.22, which is taken from the *Goddard Institute for Space*

Studies web page on stratospheric aerosol optical thickness[59]. The figure shows the zonal-mean optical thickness (at 550 nm) of stratospheric aerosols from 1850 to 2000; these data are described in *Sato et al. (1993)*. Note the increase in optical thickness, to levels above the background amount, from 1960 onwards. Optical thickness is especially high after 1963 due to the eruption of Agung (*Toon and Pollack, 1982*). This period coincides with the onset of the geomagnetic forcing of atmospheric circulation. Stratospheric optical thickness remains elevated from 1963 to 1999 due to the subsequent eruptions of Fernandina, in the Galapagos, in 1968, El Chichon in 1982, and Pinatubo in 1991 (*Sato et al. 1993*).

As well as the temporal coincidence between the geomagnetic-climate relationship and the onset of heightened stratospheric aerosols, there are numerous physical processes involving the stratospheric aerosol layer that can possibly explain why stratospheric aerosols could be crucial to the relationships described in chapter three. These include:

1. the direct influence of stratospheric aerosols on the radiative balance of the troposphere (*Toon and Pollock, 1982*),

2. the influence of stratospheric aerosols on the stratospheric latitudinal temperature gradient and subsequently tropospheric circulation (*Robock, 2001*),

3. the influence of stratospheric aerosols on ozone in the stratosphere (*Pueschel, 1996*),

4. the possibility that stratospheric aerosols are significant agents of cloud nucleation (*Dickinson, 1975*),

5. and the probable importance of stratospheric aerosols to the global electric circuit (*Engfer and Tinsley, 1999*; *Rycroft, 2000*).

The analyses performed so far in this chapter, however, have ruled-out a number of ways in which stratospheric aerosols may be important. Cloud-cover changes have been ruled-out as a likely mechanism, meaning that while points four and five may be relevant to other solar-climate relationships, they play no part in the geomagnetic

[59] http://www.giss.nasa.gov/data/strataer/

activity forcing of atmospheric circulation. Stratospheric aerosol modulation of ozone concentrations (point three) may be relevant, but the suitability of this mechanism is difficult to determine given the uncertainties of a link between geomagnetic activity and ozone. The fact that geomagnetic activity is not a viable proxy for solar irradiance variations means that the direct aerosol effect (point one), whereby stratospheric aerosols absorb and scatter incoming solar radiation (*Lohmann and Feichter, 2001*), does not form part of the required mechanism.

Instead of modifying the solar irradiance flux, which then interacts with stratospheric aerosols, it may be that geomagnetic activity influences stratospheric aerosol concentrations. A number of researchers have suggested that the cosmic ray[60] flux can impact upon stratospheric aerosols, affecting aerosol size (*Dickinson, 1975; Roldugin and Vashenyuk, 1994*) or chemical composition (*Pudovkin and Babushkina, 1992a, 1992b*). It is important to note that most research examines the link between solar cosmic rays and aerosols, not galactic cosmic rays. This is despite the fact that the particle energies associated with solar cosmic rays are typically an order of magnitude less than galactic cosmic rays and are not as important as a source of ionisation in the lower atmosphere (*Dickinson, 1975*). This means that the relationship between solar cosmic rays described in the literature may differ to the influence that galactic cosmic rays have on aerosols and the modulation of galactic cosmic rays is better represented by geomagnetic indices than the flux of solar cosmic rays.

It is therefore worthwhile examining whether there is a relationship between stratospheric aerosols and geomagnetic activity, especially since the bulk of studies consider only daily timescales. This was tested by correlating monthly stratospheric aerosol optical thickness, obtained from the *NASA Goddard Institute for Space Studies*[61], to the monthly geomagnetic AA index. The aerosol data are available from 1850 to 2000, but the correlations were performed separately for the periods 1868 to

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[60] The cosmic rays generally considered to affect stratospheric aerosols include both solar cosmic rays (associated with solar proton events) and galactic cosmic rays, which are modulated by geomagnetic activity.

[61] http://www.giss.nasa.gov/data/strataer/

1962 and 1965 to 1992. Years in which volcanic activity clearly dominated the aerosol record (1963-65, 1982-84, 1991-92) were not included in the calculations.

The results, shown in Figure 5.23, indicate that stratospheric aerosol optical depth is not modulated by geomagnetic activity, either before or after 1965. The correlations are consistently very low, and do not exceed ±0.36 for any month. There are 95 observations in the correlations for the earlier period (1868 to 1962), so a coefficient of 0.20 is required for statistical significance at the 95% confidence level. Although the results for March, August, November, and December are statistically significant they are only just so – their limited magnitude does not suggest a link to geomagnetic activity. More importantly, the correlations for the latter period, which is most relevant to the relationship in chapter three, are all statistically and practically insignificant. It is clear then that, on annual timescales, stratospheric aerosols are not modulated by geomagnetic activity to an extent that could explain the relationship in chapter three.

With the exception of point two, all of the possible stratospheric influences listed previously have been excluded as suitable mechanisms. Point two seems viable, but is difficult to test. Stratospheric aerosols themselves are known to influence the meridional temperature gradient of the stratosphere, subsequently changing tropospheric circulation (*Robock, 2001*). The geomagnetic activity influence on the stratospheric meridional temperature gradient operates in the same manner and may subsequently be amplified by the aerosol influence. Without stratospheric aerosols initially establishing a meridional temperature gradient that exceeds some threshold, geomagnetic activity effects may not be enough to overcome internal processes in stratospheric circulation. Essentially, geomagnetic activity may be 'piggy-backing' on stratospheric aerosol induced circulation changes.

Alternatively, polar winter ozone changes may be radiatively relevant by scattering high-incident solar irradiance into the pole through the twilight effect[62]. *Belikov (2000)*

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[62] The twilight effect involves the increase in ultraviolet radiation reaching the surface due to scattering from high altitude stratospheric aerosols at large solar zenith angles (*Davies, 1993; Tsitas and Yung, 1996*)

has indicated that the presence of an aerosol layer between 27.5 and 37.5 km can amplify the solar UV flux into the polar stratosphere when the solar zenith angle is close to (but less than) 90°. If these conditions are met during December and January, then the geomagnetic activity-temperature correlations evident in the polar stratosphere may be modulated by the presence of aerosols. This would subsequently explain the temporal aspect of the relationship (at least for the northern hemisphere) because the required stratospheric aerosol layer is not evident before the 1960s.

5.5.4 Upper atmosphere

The reality of geomagnetic activity induced changes in the upper atmosphere "…cannot be questioned" (*Laštovička, 1996*; page 839). Do the stratospheric changes identified in previous sections originate from the upper atmosphere? Although a number of researchers have suggested that coupling between the upper and lower terrestrial atmosphere is a viable solar-climate mechanism (see, for instance, *Geller and Alpert, 1980* and *Fuller-Rowell et al., 1997*), such a sequence of events has not yet been demonstrated. This is largely due to a lack of observational data, which also restricts the analyses of this chapter and makes it difficult to either eliminate or accept the role of the upper atmosphere in the geomagnetic forcing of atmospheric circulation. The upper atmosphere may influence the middle and lower atmosphere either through the direct penetration of vertical winds from the thermosphere to the troposphere (*Bucha and Bucha, 1998, 2002; Bucha, 2002*), or the coupling between circulation in the mesosphere and the stratosphere (*Arnold and Robinson, 1998, 2001; Fuller-Rowell et al., 1997*).

Vertical winds

The 'vertical wind' mechanism, described in *Bucha and Bucha (1998, 2002)* and *Bucha (2002),* may be the most pertinent to the results of this thesis because it is the only mechanism, so far, to be suggested specifically for the link between geomagnetic activity and the North Atlantic Oscillation. Bucha and Bucha's mechanism has been described earlier within this chapter and involves a time delay between vertical wind changes in the thermosphere and the subsequent tropospheric changes ranging from ‘nearly immediately’ to 10 days.

Smith (1998) reports that the greatest vertical winds are observed in the polar regions and are associated with auroral disturbances and divergent flow. Furthermore, the meridional scope of the vertical wind activity extends equator-ward with increased geomagnetic activity *(Smith, 1998)*. Therefore, it is generally accepted that geomagnetic and solar activity influence vertical winds in the thermosphere and mesosphere. There is no indication, however, that vertical winds are relevant to the lower atmosphere through direct propagation, in either observational data or models. A mechanism by which geomagnetic or solar activity influences the troposphere through the direct penetration of vertical winds into the lower atmosphere is therefore discounted because, given the relative disparity between the mass and density of the thermosphere and the lower atmospheric layers (displayed in Figure 2.9), it is unlikely that thermospheric winds can impact significantly upon the troposphere. *Arnold and Robinson (1998)* report, “The amplitude of any disturbance propagating downwards in the atmosphere is reduced by a factor of ten over a couple of scale heights due to the exponential rise in pressure towards the surface…” (page 70). In fact, it is generally acknowledged that some form of amplification is needed before solar activity can account for observed climate changes (*Tinsley, 1996a*). The geomagnetic activity-related changes in tropospheric circulation described in chapter three are not small, whereas one can assume that if thermospheric winds did impact upon the troposphere the magnitude of this effect would be reduced by the downward propagation of the winds into denser atmospheric layers.

Atmospheric coupling

Geller and Alpert (1980) used a planetary wave model to conclude that mean zonal wind changes at a height of roughly 35 km (or lower) would result in changes to tropospheric planetary wave patterns. In essence, their findings are similar to the stratosphere-troposphere coupling described by numerous researchers (e.g., *Baldwin and Dunkerton, 1999, 2001; Thompson et al., 2002*), except that in their model the interaction with upward propagating planetary waves occurs at a higher altitude. The stratosphere-troposphere coupling observed within this chapter, however, is evident in the lower stratosphere.

It is possible, however, that the stratospheric changes originated higher up, perhaps even in the thermosphere or mesosphere. Unfortunately, a lack of observational data for the upper and middle atmosphere makes it difficult to test such a hypothesis directly. The best available data, the *Upper Atmospheric Research Satellite (UARS)* data[63], currently only extends from late 1991 onwards. Therefore, the *UARS* zonal-mean zonal wind data does not cover even a complete solar cycle, and only shares six (1992-1997) years with the *NCEP/NCAR* reanalysis data used in section 5.4. It is not possible, therefore, to evaluate this mechanism using a long record of observational data.

Nevertheless, there is strong evidence to support a mechanism in which the upper atmosphere is coupled to the middle atmosphere. Using a mechanistic three-dimensional model, *Arnold and Robinson (1998, 2001)* have demonstrated that the solar influence on the thermosphere is coupled to the stratosphere via planetary waves. Specifically, *Arnold and Robinson (2001)* reveal that the thermospheric impact of the solar wind (*i.e.*, geomagnetic activity) is relevant to the stratosphere through non-linear forcing. In particular, geomagnetic forcing of the lower thermosphere inhibits the winter latitudinal transport of the stratosphere, cooling the stratospheric polar vortex during winter (*Arnold and Robinson, 2001*). This allows geomagnetic activity to impact upon the NAM through the stratosphere-troposphere coupling described earlier. The amplification of the impact of geomagnetic activity with decreasing altitude, inferred from the correlations presented earlier in this chapter, is evident in the modelled results of *Arnold and Robinson (2001)*.

The model employed by *Arnold and Robinson (1998)* has a horizontal resolution of 5° and a vertical resolution of roughly 2 km in the middle atmosphere. Geomagnetic activity was kept at ‘quiet’ conditions throughout the simulation, while solar flux conditions were allowed to vary in order to represent solar maximum and minimum

[63] See *Swinbank and Ortland (2000)* and http://www.sparc.sunysb.edu/html/urap.html

conditions (*Arnold and Robinson, 1998*). They found little difference between solar minimum and maximum forcing in the summer hemisphere, whereas the northern winter hemisphere displayed pronounced differences between the two states, including a change in zonal-mean zonal wind of ~20 ms^{-1} at the edge of the winter vortex. Based on the results of the model, *Arnold and Robinson (1998)* concluded that the longer radiative timescales associated with winter allow planetary wave effects in the thermosphere to accumulate, which then subsequently ‘feedback’ onto stratospheric circulation via further planetary wave activity.

The suitability of this mechanism to the relationship described within this thesis is further evident when the results of *Arnold and Robinson (2001)* are considered. *Arnold and Robinson (2001)* used a similar model as the one in *Arnold and Robinson (1998)*, but this time performed a series of simulations for varying geomagnetic activity conditions, ranging from Ap values of one to 61. Figure 5.24 shows the 10-day mean zonal average differences in temperature and zonal wind, derived from their model, associated with varying geomagnetic activity conditions (from their figures 1 and 2). Note, in 5.24a, the temperature decrease in the northern polar region at an altitude ~35 km of up to 4°K. Outside of this area, and below 60 km altitude, temperature changes are minimal. Compare now the result of *Arnold and Robinson (2001)* shown in Figure 5.24a with Figure 5.12, which shows a December decrease in temperature of ~5°K concentrated at the northern polar area, at an altitude of 25 km. Outside of this region temperature changes associated with geomagnetic activity are negligible. The modelled results of *Arnold and Robinson (2001)* and the observations presented in Figure 5.12 for December differ only in the altitude of the temperature changes. Although the observational results presented in this chapter, derived using the *NCEP/NCAR* reanalysis data, are limited to altitudes below 30 km, the spatial pattern of the northern polar vortex temperature response to geomagnetic activity shows a strong similarity to the modelled results.

This similarity is also evident for the zonal-mean zonal wind composites shown in Figure 5.4, for December, and the *Arnold and Robison (2001)* model results shown in Figure 5.24b. The model results show an increase in zonal-mean zonal wind, of up to 7 ms^{-1} around 40°N (*Arnold and Robinson, 2001*). The strengthening of zonal wind extends down to ~40 km in altitude, and poleward nearly to 90°N. The positive changes associated with geomagnetic activity in the model are flanked to the south by minor decreases of zonal-mean zonal wind of ~2 ms^{-1}, also extending down to an altitude of ~40 km. The December results in Figure 5.4 also show a dipole-like pattern of zonal-mean zonal wind differences, with a negative response south of 45°N ranging up to ~4 ms^{-1} and a positive response centred on ~65°N which exceed 13 ms^{-1}. Although the observed differences presented in this thesis occur lower in the atmosphere and are of higher magnitude than the modelled differences of *Arnold and Robinson (2001)*, the spatial similarities strongly support the conclusion that coupling between the upper and middle atmosphere is the source of the stratospheric signature of geomagnetic activity discerned within this chapter.

The differences between the altitudinal pattern of the observed and modelled results may be due to the role that stratosphere-troposphere coupling plays in the winter stratosphere, or could be a result of the limitations of the model used in *Arnold and Robinson (1998, 2001)*. How can this mechanism accommodate the temporal pattern and the possible role of stratospheric aerosols? *Arnold and Robinson (1998)* indicated that "The level of planetary wave activity is shown to be a key process in determining the extent to which the stratosphere is able to respond to changes in the lower thermosphere." (page 74). Based on the results of this chapter, it is therefore hypothesized that the presence of stratospheric aerosols, which increases the latitudinal temperature gradient of the stratosphere (*Robock, 2001*), strengthens the polar vortex. This subsequently should allow stronger planetary wave propagation from the stratosphere into the upper atmosphere, thereby increasing the stratospheric response to thermospheric changes. A similar concept facilitates the QBO east phase modulation of the relationship by allowing tropospheric planetary wave activity to propagate higher (and more poleward) into the stratosphere. The temporal pattern of the correlations in chapter three is therefore the result of stratospheric aerosols allowing the stratosphere and mesosphere/thermosphere to couple to such an extent that geomagnetic activity changes become relevant to the lower atmosphere. Without stratospheric aerosols 'priming' the stratosphere for planetary wave propagation into the thermosphere it may be that the coupling of the upper and middle atmospheres described in *Arnold and*

Robinson (1998, 2001) is not strong enough to allow geomagnetic activity effects to overcome some threshold below which a tropospheric response is lacking.

5.6 Discussion

The zonal-mean correlations presented within this chapter were performed to evaluate mechanisms and to a lesser extent, verify relationships in chapter three. They can also be viewed, however, as solar-climate studies within themselves. The availability of the *NCEP/NCAR* reanalysis data presents a unique opportunity for solar-climate researchers to examine spatial patterns of potential relationships. In this case, changes in zonal-mean zonal wind and temperature were evaluated, for each month separately, from the surface to altitudes of approximately 30 km. The scope of this study is therefore relatively large, especially when compared to studies that use indices alone to parameterise atmospheric changes. It must remembered, however, that if the results of chapter five are to be used as observational evidence of a solar climate relationship then the statistical significance must be adjusted accordingly to accommodate serial correlation. This is an overwhelming task, as there are 1,241 correlations for each month, each with its own N_{eff}, and there are over 110 'months' of correlations, meaning that over 136,510 N_{eff} values would have to be calculated and the statistical significance of each one represented individually within the appropriate figures.

Since the relationship between geomagnetic activity and annular modes described in this thesis is novel, none of the mechanisms found in the current literature are perfectly suited to the relationships. Figure 5.25 presents an updated schema of possible mechanisms for both the southern and northern hemispheres, even though it is clear that different mechanisms operate between the hemispheres. In Figure 5.25, the most likely mechanism has been highlighted in green. The analyses of this chapter have been successful in constraining potential mechanisms and excluded some mechanisms based on the insights discovered herein. The figure acknowledges that geomagnetic activity influences tropospheric climate via stratospheric circulation. The role of the stratosphere in the southern hemisphere is different, largely because it does not involves the polar vortex and is not as obvious in the results.

In the northern hemisphere during the early winter, geomagnetic activity induced changes to the meridional temperature gradient of the stratosphere, especially evident in the polar vortex, alters the zonal wind regime at the edge of the polar vortex (~60°N). During January, when the stratosphere and troposphere are coupled, the zonal wind changes propagate to the troposphere and influence the Arctic Oscillation. This link only occurs during the east phase of the QBO because planetary waves are propagating higher into the atmosphere during this phase and therefore interacting better with the stratospheric changes, or possibly because the December changes in the stratosphere are maintained/supported by the QBO east phenomenon. Once the stratosphere and troposphere are coupled in January, the geomagnetic influence on the stratospheric polar vortex is lost to the effect of upward propagating planetary waves. The geomagnetic signature is therefore shifted polewards in February and not evident in later winter months. This indicates that geomagnetic activity influences the stratosphere only in the early boreal winter, and does not renew its influence on the lower atmosphere throughout the rest of the winter. The source of the December/January stratospheric temperature changes (which occur in the southern hemisphere as well) can confidently be attributed to coupling between the upper atmosphere and the middle atmosphere, as described in *Arnold and Robinson (1998, 2001)*.

In Figure 5.25, the alternative source of the stratospheric circulation changes, that geomagnetic activity is directly or indirectly influencing ozone concentrations within the polar vortex, has been left open as a possibility because of the vague and contradictory nature of geomagnetic-ozone studies. If it is assumed that geomagnetically-induced ozone changes are responsible for stratospheric zonal-mean zonal wind and temperature changes associated with geomagnetic activity then the stratospheric aerosol ‘twilight effect’ can explain the temporal pattern. In this scenario, the seasonal aspect of the northern hemisphere results is partly due to the solar zenith angle required, the twilight effect being suitable only in winter. Overall, however, this mechanism is much less refined than the previously described one and while it warrants further investigation and modelling, it is not the preferred explanation for the relationship described in chapter three.

In the southern hemisphere, it seems that ozone may play an important role in the geomagnetic activity coupling to the troposphere, despite the fact that the link between geomagnetic activity and ozone is ambiguous and unclear. The reasons for this have been mentioned previously. The appropriate mechanism is described in *Haigh (1996)* and has been reviewed in earlier sections of this chapter. The Haigh mechanism is more viable than the ozone forcing via the southern stratospheric polar vortex described in *Thompson and Solomon (2002)*, largely because a strong geomagnetic activity signature is not seen at the southern pole. The main limitation of both mechanisms is their inability to explain the temporal pattern of the correlations in the southern hemisphere. Unless stratospheric aerosols play some part in facilitating the geomagnetic influence on ozone, or prime stratospheric circulation in some way that makes it receptive to geomagnetic activity changes, it is difficult to accommodate the temporal inconsistency of the correlations. The seasonal pattern is also difficult to explain. The ozone induced changes outlined in *Thompson and Solomon (2002)* are restricted to the stratosphere during March and impact on the troposphere during April and May. The Haigh mechanism has been described only during January. Therefore, neither mechanism accommodates the March tropospheric correlations perfectly.

The alternative explanation is that the geomagnetic activity signature in the southern hemisphere is the result of the large-scale circulation changes associated with the solstice circulation in the middle and upper atmosphere. Once again, however, it is difficult reconciling this scenario with the seasonal and temporal aspects of the results. Future research would be best directed at determining if the southern hemisphere effect is real, before employing any further effort on potential mechanisms.

5.6.1 Prediction

Scientific prediction has two main uses, validation and guidance (*Sarewitz and Pielke, 1999*); it serves as a test of scientific hypotheses and as a guide for decision-making. In this latter scenario, climate prediction has the potential to provide significant socio-economic benefits especially in agricultural endeavours (*Jones et al., 2000; Ogallo et al., 2000*). The successful application of solar-climate relationships to the prediction of climate change, on either daily, seasonal, interannual, or long-term timescales would confirm the reality of the relationships, many of which are controversial, and if successfully applied to agricultural or ecological systems, it would confirm their practical significance.

This section examines the predictive value of the relationship described in this thesis. In hindsight, one example of the predictive potential for this relationship involves the interplay between decadal and interannual variability. For example, the uncharacteristically low NAO index values between 1995 and 1997 (refer to Figure 3.3) have prompted the mistaken speculation that the recent NAO warming has ended, and that the NAO may have switched to a cool (low index) regime (see, for instance, *Keller, 1999*). This is clearly a case where the knowledge that geomagnetic activity significantly forces the NAO at decadal and interannual timescales is of benefit. Knowing that the average annual AA index value was also lower than usual for those years, and that a geomagnetic activity maximum was approaching, suggests that it is presumptuous to assume a long-term shift in the NAO because a decadal maximum in NAO values should have occurred.

Of course, there are other possible explanations for the behaviour of the NAO at interannual timescales. *Dong et al. (2000)*, for instance, attribute the change in North Atlantic climate, between 1997/1998 and 1998/1999, to sea surface temperature changes associated with ENSO. Although sea-surface temperature changes do not necessarily explain the earlier low NAO index values in 1996/1997, this example shows that the somewhat limited (both in magnitude and seasonality) correlation between geomagnetic activity and the NAO means that other causes cannot automatically be ruled out. Furthermore, it demonstrates that atmosphere-ocean coupling, such as sea surface temperature forcing, may also be an important source of interannual variations in the NAO. It is therefore worthwhile comparing, in retrospect, the usefulness of geomagnetic forcing to that of ocean forcing for the prediction of the North Atlantic Oscillation.

This analysis is performed by comparing, in hindsight[64], the predictive usefulness of the geomagnetic activity index to the results of *Rodwell et al. (1999)*, who used a general circulation model (GCM) of the atmosphere over the north Atlantic and Europe to examine the use of sea surface temperatures for decadal and interannual prediction. Focusing on the December to February season, they simulated atmospheric conditions in response to ocean forcing from 1947 to 1997. Their simulated NAO index correlates well with the observed NAO, $r = 0.41$ for the original (unfiltered) curves and $r = 0.74$ for decadal variations. How do these correlation coefficients compare to those for the AA-NAO and AA-NAM indices for the same period?

Correlations between the original and decadal variations, for the same period and calculated in the same manner, are shown in Table 5.5. Note that *Rodwell et al. (1999)* derived their decadal variations using a 1-2-1 binomial filter, applied to the original data three times – the same filter was used here in constructing Table 5.5. The table shows the DJF seasonal value, to compare with that of *Rodwell et al. (1999)*, as well as the JFM value, for which the AA-NAO/NAM relationship is strongest. Although somewhat diminished from the values presented in chapter three, the correlations between the geomagnetic AA and NAO indices are roughly equivalent to those between the simulated NAO index of *Rodwell et al. (1999)*, which incorporate ocean-atmosphere interactions involving sea surface temperature and sea ice concentration feedbacks, and the observed NAO. The JFM AA-NAO correlation is larger ($r = 0.49$) than the sea surface temperature forcing for DJF. Furthermore, the QBO modulation of the geomagnetic forcing has not been incorporated into these analyses, thereby limiting the magnitude of the interannual correlations. Allowing for serial correlation, the decadal correlations with the AA index are not significant at the 95% confidence level, while *Rodwell et al. (1999)* state that, allowing for persistence, their decadal correlation is significant at the 99.9% confidence level. Despite the contrast in the statistical significance of the results, the magnitude of the decadal correlations is also similar.

[64] Known as ‘retrodiction’ (*Sarewitz and Pielke, 1999*)

Table 5.5. Comparison of the correlation coefficients between the observed NAO index and both the simulated NAO index of *Rodwell et al. (1999)* and the geomagnetic AA index. The table shows that the predictive value of the AA-NAO relationship is about as good as current methods based on sea surface temperatures. Note the similarity in the magnitude of the correlation coefficients for Rodwell's modelled NAO and geomagnetic activity. Correlations that are significant at the 95% confidence level, allowing for the effective number of observations due to serial correlations, are in bold.

Indices	Interannual	Decadal
DJF Simulated NAO (1947-1997) (*Rodwell et al., 1999*)	**0.41**	**0.74**
DJF AA index (1947-1996)	**0.38**	0.70
JFM AA index (1947-1996)	**0.49**	0.73

The correlations presented here represent a relationship that affords a predictive ability for the NAO that is about as good as current simulations. The main drawback, however, is that interannual changes in geomagnetic activity are not as predictable as sea surface temperatures. The role of the QBO in modulating the geomagnetic influence will also limit the predictive value of the relationship. The dependence on the QBO east phase means that interannual variations in the NAO cannot be predicted for all years. Furthermore, the sea surface temperature forcing of the North Atlantic Oscillation is not temporally restricted, while geomagnetic forcing of atmospheric circulation appears to be an intermittent phenomenon. These are just some of the many points that limit the predictive value of the relationship described in this thesis. Other factors include the difficulty with predicting or modelling geomagnetic activity, the uncertainties relating to the appropriate solar-climate mechanism, which at this stage make it difficult to model geomagnetic forcing of the atmosphere, and the lack of a detectable relationship between geomagnetic activity and atmospheric circulation at daily timescales.

In September 1996, the *NOAA Space Environment Center* and the *NASA Office of Space Science* commissioned a scientific panel to evaluate prediction techniques for the coming solar and geomagnetic maximum (*Joselyn et al., 1996*). The panel's objective was to "…predict the approximate total number and annual number of significant geomagnetic disturbances during Cycle 23." (*Joselyn et al., 1996*; page 4), an objective they state that "is not widely studied in the scientific community." (page 4). It can be noted, therefore, that while there are considerable efforts to predict geomagnetic activity at very short timescales[65], there is not as much interest in the prediction of long-term changes in geomagnetic activity. *Lundstedt (1996)* indicates that the use of artificial neural networks is optimal, allowing for geomagnetic activity predictions up to 29 days in advance. Further advances in geomagnetic activity prediction may therefore increase the practical value of the relationship described in this thesis.

One aspect of the results that might successfully be exploited is the serial correlation in the AA index, described in Table 5.1. Remembering, for example, that in the northern hemisphere the geomagnetic forcing of atmospheric circulation is restricted to January in monthly data, it may be possible to use the serial correlation in the monthly AA index, centred on January, for prediction purposes. Table 5.6 shows the correlation coefficients between the January AA index and all other months, up to 12 months lag.

The relatively high correlations suggest that some notion of January geomagnetic conditions can be formed a number of months in advance, especially over one to three months lag. Furthermore, the table shows that it can be determined, with a ~77% success rate, whether or not the January AA value will be above or below the long-term mean (19.3 nT) based on the monthly AA value over a number of months lag. For example, the table indicates that in 72% of cases, when the July AA index was above 19.3 nT, the AA index of the following January was also above 19.3 nT, and vice versa. When extrapolated to changes in the actual NAO index, however, this technique only picks the correct sign between 51% and 71% of the time. These percent of successful 'predictions' are shown in Table 5.6 and were calculated by comparing instances when the January NAO index was above or below the mean[66] NAO value (-0.10), to whether the AA index, for various months at lag, was also above or below the mean. The months of October and June show some potential for the prediction of the sign of the January NAO index relative to the 1965-2000 NAO mean. The results of a one-sample sign test (shown in Table 5.6) indicate a reasonable level of statistical significance (ρ = 0.017)

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[65] See, for example, the review in *Lundstedt, 1996* and the *Chen IMF Prediction project* at http://sec.noaa.gov/chen/index.html

[66] From 1965 to 1998

associated with this crude prediction technique. The success of this technique is even greater when only years of QBO east data are considered. Using AA index values for either December or June allow a prediction rate of 88% when determining if the NAO index values for the following January will be above or below the mean. The rate of success based on these two months is greater even than the 75% achieved when January values from the previous year (*i.e.*, one-year's lag) are used. The link between December and January AA index values, and subsequently NAO index values, is a simple function of the serial correlation in the AA index and the strong decadal signal. The link between the June AA index values and the December values is probably related to the semi-annual variation of geomagnetic activity, which is centred (approximately) on the 25th of June and the 26th of December (*Cliver et al., 2002*).

Overall, however, there are several limitations preventing the use geomagnetic activity variations, at various timescales, for climate prediction. This is despite the fact that chapter three has thoroughly examined many aspects of the relationship. The main limitation relates to uncertainties regarding the appropriate mechanism and therefore the temporal pattern of the relationship.

Table 5.6 Rate of success for a crude prediction technique based on annual monthly AA index anomalies, and the serial correlation in the monthly AA index. The table demonstrates that the relationship described in chapter three has some predictive value, which warrants further investigation. The probability that each percentage has occurred due to chance is shown in the bottom row. The percentage values indicate the success at forecasting whether the January AA or NAO indices will be above or below the overall respective mean, based on the AA value of previous months. Note, for example, that the value of the NAO relative to the mean can be predicted 71% of the time using the June AA index value.

Month Lag	Dec *1*	Nov *2*	Oct *3*	Sep *4*	Aug *5*	Jul *6*	Jun *7*	May *8*	Apr *9*	Mar *10*	Feb *11*	Jan *12*
r	0.67	0.55	0.65	0.51	0.55	0.46	0.55	0.50	0.51	0.48	0.45	0.38
AA Above/Below (Mean Prediction Success Rate)	73%	79%	73%	69%	72%	72%	74%	73%	66%	67%	66%	64%
NAO Above/Below (Mean Prediction Success Rate)	66%	69%	71%	57%	57%	63%	71%	63%	51%	51%	51%	66%
ρ (n = 35)	.0895	.0410	.0167	.4996	.4996	.1755	.0167	.1755	>.9999	>.9999	>.9999	.0895

5.6.2 Causality

Tropospheric processes can influence the earth's magnetic field. *Karinen et al. (2002)* investigated the 'weekend effect' in the magnetosphere, where differences in power consumption on the weekends are manifested in the magnetosphere due to power line harmonic radiation. Although they conclude that there is no evidence for such an effect, the notion that anthropogenic activity at the earth's surface can influence the magnetic field raises questions about the order-of-effect for the results in chapter three. Even more problematic to the causality of the relationship is the fact that tropospheric and stratospheric circulation, in particular planetary wave activity, is manifested in indices of geomagnetic activity. *Kohsiek et al. (1995)* performed Fourier analyses on geomagnetic data from the mid-latitude northern hemisphere and found 10- and 16-day periodicities associated with planetary wave activity. Furthermore, *Geller and Alpert (1980)* indicated that changes in thermospheric wind below heights of 110 km result in changes in geomagnetic activity through dynamo action. *Abraham et al. (1997)* presented results indicating that the stratosphere and mesosphere are coupled by the QBO, and that the QBO in mesospheric winds is anti-correlated to the QBO in the stratosphere. *Olsen and Kiefer (1995)* described the influence of the QBO on lower thermospheric winds and geomagnetic variations, and noted that changes in zonal wind can explain the presence of a 27-month cycle in geomagnetic activity. *Jacobi and Beckmann (1999)* demonstrated that, between 1979 and 1996, January-February mesopause zonal winds over Collm (15°E, 52° N) are strongly correlated (r = 0.70) to the North Atlantic Oscillation. These findings show that changes in tropospheric and stratospheric circulation are manifested in the mesosphere and thermosphere, where they can influence geomagnetic activity through the dynamo effect.

Although it is therefore clear that, to some degree, changes in geomagnetic activity result from planetary wave activity, this does not compromise the relationship described in chapter three. This study has used the AA index as a measure of geomagnetic activity. The AA index is a 'planetary-scale' index of geomagnetic activity (*Ahn et al., 2000*) and being antipodal, changes associated with planetary wave activity have a limited impact on the index because they are not mirrored in both hemispheres. That is, local changes in geomagnetic activity due to mesopause winds will not be manifested in the AA index unless these changes are the same at both Hartland, in England, and Canberra, in Australia. Furthermore, dynamo effects due to mesospheric winds sourced from the lower atmosphere should be minor, if not negligible, compared to solar effects on the AA index. The dominant impact on geomagnetic activity is solar variability, as evidenced by the correlation of geomagnetic activity to the sunspot number and the importance of solar events to the state of the geomagnetic field. The findings of *Kane (1995)* support this view. Although *Kane (1995)* found a QBO signal in ionospheric parameters (and planetary geomagnetic activity) that is roughly similar to the 50 hPa atmospheric QBO, he concluded that the major variations in ionospheric parameters are nevertheless associated with the solar cycle.

The following analyses support this view. By correlating the QBO index to the geomagnetic AA index for January (when the AA/NAM relationship is strongest) it is clear that the relationship between the two geophysical parameters is negligible. When both QBO east and west data are included, the correlation coefficient between the AA index and the QBO is 0.12 (N = 33), which is not statistically significant at the 95% confidence level. Restricting the analyses to QBO east data only, which strengthens the AA/NAM correlations, also yields a non-significant correlation (r = 0.33, N = 15). This confirms the causality of the results in this thesis, and excludes a common QBO signal in January NAM and AA indices as an explanation for the results. Essentially, it reveals that changes in mesospheric wind associated with the QBO do not significantly impact upon the AA index.

The most convincing evidence that the cause-and-effect ordering assumed within this thesis is correct, however, is the seasonal pattern in the results for the northern hemisphere data. The geomagnetic activity signature occurs first in the December stratosphere and then in January in the tropospheric circulation. Even in November, zonal-mean temperature in the stratosphere of both hemispheres displays some correlation to geomagnetic activity, well before any tropospheric correlations are evident. This demonstrates that geomagnetic activity is forcing atmospheric circulation and not vice versa.

5.7 Conclusion

The relationship between geomagnetic activity and atmospheric circulation has the right cause-and-effect ordering to indicate that changes in solar activity, which are manifested as geomagnetic activity, impact upon atmospheric circulation and not vice versa. Subsequently, the geomagnetic activity signatures in zonal-mean zonal wind and temperature have confirmed the major findings of chapter three. Furthermore, the geomagnetic forcing described in this and other chapters has predictive value on both interannual and decadal timescales. This predictive value is tantamount to that associated with atmosphere-ocean forcing of the NAO (*Rodwell et al., 1999*), but is severely limited by the inconsistencies in the geomagnetic forcing of climate and the modulating effect of the QBO.

In terms of mechanisms, it is clear that the stratosphere-troposphere coupling plays an important role, while the ever-popular cloud-cover mechanisms (*Veretenenko and Pudovkin, 1995; Tinsley, 1996a, b; Svensmark and Friis-Christensen, 1997*) are irrelevant to the geomagnetic forcing of recent climate change. At least in the northern hemisphere, the geomagnetically-induced stratospheric circulation changes are sourced from the upper atmosphere (in the manner outlined in *Arnold and Robinson, 1998, 2001*), which is known to undergo large-scale changes in response to geomagnetic activity variations (*Fuller-Rowell et al., 1997*). Both the upper atmosphere circulation and ozone changes may also be relevant to the geomagnetic activity forcing of the Antarctic Oscillation.

Surprisingly, geomagnetic activity is not correlated to solar irradiance on monthly or daily timescales, which conflicts with one of the more commonly held notions that geomagnetic activity is a proxy of solar irradiance variations (*Cliver et al., 1998*). Furthermore, there is no evidence of a geomagnetic activity, and hence cosmic ray, influence on stratospheric aerosols at monthly timescales. Links between geomagnetic (or cosmic-ray) activity and ozone are unclear and warrant careful consideration in future studies.

6 Summary and Conclusions

6.1 Original contributions

Geomagnetic activity is generally not the index of choice for solar-climate researchers wanting to parameterise solar variability. Accordingly, the findings of this thesis contribute to a new understanding of solar-climate relationships. Rigorous statistical analyses have confirmed that geomagnetic activity influences atmospheric circulation in the northern hemisphere, as represented by the Arctic and North Atlantic Oscillations. Furthermore, it was revealed that geomagnetic activity is also relevant to the Antarctic Oscillation index in the southern hemisphere. Correlation coefficients between geomagnetic activity and atmospheric circulation indices are statistically significant despite the effects of serial correlation, and are evident at both decadal and interannual timescales. Furthermore, the magnitude of the correlations warrants the suggestion that the relationship is of practical significance to climate change.

There are specific features of these relationships that were not previously known, and indicate that the geomagnetic influence is different between the southern and northern hemispheres. In the northern hemisphere, there is evidence that the QBO modulates the relationship, which is discernable when the data are separated according to the phase of the QBO. A QBO influence is not evident in the southern hemisphere. Furthermore, geomagnetic activity has a strong signature in the lower stratosphere of the northern hemisphere, specifically during winter (DJF) months. A geomagnetic activity signature is lacking in the southern hemisphere stratosphere, which is instead found in the troposphere during March. Together, these points illustrate the fundamental interhemispheric differences that exist between the geomagnetic forcing of atmospheric circulation. The northern hemisphere relationship is a December-January phenomenon, in which the stratospheric polar vortex plays an important part and utilises stratosphere-troposphere coupling to influence atmospheric circulation in the troposphere. The southern hemisphere relationship is an autumn phenomenon, though the geomagnetic activity signature in the September zonal-mean data suggests it may be an equinoctial occurrence, and a stratospheric contribution is not obvious. In both cases, ozone changes induced by geomagnetic activity may also form part of the mechanism.

The research within this thesis has also addressed some of the technical recommendations and key scientific questions listed in the *NASA Workshop on Sun-Climate Connections (Summary Report)*, held during March 2000. Specifically, recommendation 3.2E, which states that “The effects of solar variability must be studied location-by-location and season-by-season…” (page 6), has been addressed by the spatial and seasonal analyses presented in chapters two, three, and five. Recommendation 3.2F, which indicates that there is a “…need to develop predictive capability” (page 7) has also been addressed by chapter five, though in somewhat of a different manner to the workshop recommendations. Some of the key scientific questions from the summary report sections 4.1A and 4.1C were also addressed within this thesis. Namely, the first key scientific question in 4.1A asks “What is the share between influences of changes in magnetic fields and changes in the thermal structure of the sun?” (page 8), and this has been addressed, in part, in chapter three when the correlations between geomagnetic activity and atmospheric circulation were compared to those between the sunspot number and atmospheric circulation. Questions within section 4.1C that have been addressed include “What is the geographic, vertical, and seasonal distribution of climate sensitivities and responses to direct and indirect solar forcings?” (page 11), which was addressed in chapter five, and “Are different climate responses/processes at work at different time scales of solar forcing?” (page 11), which has been addressed throughout the entire thesis.

This thesis has also contributed to the field of solar-climate studies by demonstrating the benefits associated with the examination of various aspects of climate relationships. Specifically, examining temporal, spatial, seasonal, timescale, and lagged components of relationships is fruitful and should be done for other relationships within the field. The use of cumulative sums and sliding correlations has objectively defined the temporal nature of the relationship – in both hemispheres it was found that geomagnetic forcing is largely restricted to 1963 onwards. Without considering the temporal nature of the results, the link between geomagnetic activity and the Arctic Oscillation would not be evident since correlations over the entire record are negligible. Examination of the spatial pattern of the results, especially in the manner performed in chapter five, served to either confirm of deny the relationships outlined in chapter three, which were based on indices of atmospheric circulation only. Furthermore, an understanding of the spatial pattern provided a tremendous insight into potential mechanisms, as demonstrated in chapter five. Similarly, the use of monthly and seasonal data allowed for the detection of relationships that have a strong seasonal component, which may otherwise have been overlooked in annual data. It also provided insights into mechanisms, and dispelled the notion that solar-climate relationships are purely a winter phenomenon. The examination of the relationship at various timescales (decadal, annual, daily) is more readily accomplished when geomagnetic indices, rather than sunspot or solar flux data, are used to represent solar variability. As well as assisting with investigating mechanisms, the results for various timescales allowed the predictive value of the results to be understood. Similarly, an understanding of the relationship at various lags not only helped to constrain possible mechanisms, but also proved useful for prediction.

6.2 Comparisons

The relationship described in chapter three is unique when compared to other solar-climate relationships. In their review of solar-climate relationships, *Friis-Christensen and Svensmark (1997)* suggest that the field suffers not only from the lack of a physical mechanism, but also because the solar activity parameter behind the relationships has not been identified. The results of this thesis present evidence that multiple solar activity parameters are relevant to climate change. This thesis has shown that the geomagnetic activity influence on atmospheric circulation is separate to the solar-cycle length forcing of climate and unrelated to the solar cycle forcing of the stratosphere (see Appendix E) as described in *Labitzke and van Loon (2000)*. In fact, analyses presented in chapter two have shown that the geomagnetic AA index is not a suitable proxy of solar irradiance flux at daily or monthly/annual timescales. Furthermore, results of analyses presented in chapter two comparing solar-cycle length and geomagnetic activity do not necessarily concur with the view that the solar-cycle length is "…an alternative proxy for solar magnetic activity." (*Reid, 1999*; page 10). Indices of solar-cycle length are well correlated to geomagnetic activity indices, but it is not clear whether the correlations are strong enough to suggest that the two are interchangeable.

Geomagnetic forcing of atmospheric circulation is also unrelated to the relationship between long-term temperature changes and geomagnetic activity, which does not show the same temporal, spatial, or seasonal pattern. The long-term relationship may be due to the solar irradiance forcing described in *Lean and Rind (1999)*. This is because although geomagnetic activity is not a proxy for solar irradiance on short timescales, the overall trend in solar irradiance is matched by long-term geomagnetic activity changes, even though the two are different heliophysical phenomena.

6.3 Limitations

This thesis has examined a broad range of issues in the field of solar-climate relationships and consequently has encountered numerous limitations. This section discusses the specific limitations of the research presented within this thesis, as well as the general limitations within the field.

One of the major limitations is the attempt, within this thesis, to explain the temporal pattern of the correlations in chapter three. It has speculatively been attributed to stratospheric aerosols, largely because of the temporal coincidence of both phenomena, and also because there is some theoretical backing for such a suggestion. It is also difficult to determine the solar origin of the changes observed in chapter five, and subsequently, which aspect of geomagnetic activity is pertinent to atmospheric circulation. The similarity between cosmic-ray flux, interplanetary magnetic field and solar wind variations, and sunspot and solar irradiances changes, requires careful consideration when attempting to establish which aspect of solar activity is relevant to climate. This thesis has demonstrated that the solar phenomena most commonly associated with climate change, solar irradiance and cosmic rays, are not relevant to the geomagnetic forcing of atmospheric circulation. More work in this area is required, however.

This thesis has paid particular attention to the statistical rigour of the results and, where feasible, followed Pittock's guidelines – but will it be enough to convince sceptics? *Siscoe (2000)* reports a variety of impacts that solar activity has on the 'cyberlectrosphere'. These are accepted because the cause and effect is clear and the impacts are tangible. This thesis has described a solar-climate relationship that, in addition to those already evident in the literature, suggests that solar activity has a variety of impacts of climate. The cause and effect (*i.e.*, mechanism), however, is not fully developed and the impacts are not always tangible because, as *Haigh (2001)* points out, it is difficult to separate solar effects from other climate effects.

6.4 Future research/Recommendations

The use of atmospheric models is one way in which the previously mentioned limitations might be overcome, especially with the evaluation of potential mechanisms. For other researchers, modelling has provided valuable insights into solar-climate relationships (for example, *Haigh, 1996, 1999; Arnold and Robinson, 1998, 2001; Shindell, 2001b*), and for the understanding of the annular modes (as described in *Moritz et al., 2002*). Modelling the effects of geomagnetic activity on climate should prove even more fruitful, largely because geomagnetic variations operate over broader timescales than solar cycle changes. The suitability of known geomagnetic activity impacts, such as upper atmosphere dynamic and chemical changes, could be tested using atmospheric circulation models that extend beyond the middle atmosphere down to the boundary layer. The relative importance of geomagnetic activity induced effects such as ion drag, joule heating, and chemical composition changes could then be modelled for high and low geomagnetic activity conditions. In this regard, the findings of this thesis could help to constrain and guide modelling attempts, and the zonal-mean correlations presented in chapter five represent observational results for the lower atmosphere against which model output could be verified. The use of models, therefore, should be the next step in the examination of solar-climate relationships involving geomagnetic activity.

6.5 Conclusions

Chapter three examined the possible role that geomagnetic activity has played in recent climate change via the annular modes and found that:

1. The onset of solar-modulated geomagnetic forcing of the Arctic and North Atlantic Oscillations coincides with a regime shift in northern hemisphere climate. Solar activity can therefore explain the enigmatic features of climate in the North Atlantic region since the early 1960s.

2. Interannual variations in the Arctic and North Atlantic Oscillations need no longer be considered as ‘climatic noise’. From 1965 to 1997, and for Januaries in which the QBO is eastwards, the geomagnetic AA index is highly (r = 0.85) correlated to the Arctic Oscillation, indicating that the interannual variations are not stochastic in origin.

3. Similarly, the positive trend in the Arctic and North Atlantic Oscillations, evident since the beginning of the regime change and associated with decadal variations, is also deterministic and is forced by geomagnetic activity. The uncharacteristic low in the geomagnetic AA index in the 1960s is matched by a similar period of low values in indices of the Arctic and North Atlantic Oscillations and both the AA and atmospheric circulation indices exhibit an increasing trend from that time onwards. This may mitigate, to some extent, the importance of anthropogenic forcing of Arctic and North Atlantic climate change.

4. The degree to which changes in the North Atlantic Oscillation are attributed to atmosphere-ocean coupling may also need revision, as geomagnetic activity changes are of practical importance to the North Atlantic Oscillation on both decadal and interannual timescales.

5. The geomagnetic forcing of the Arctic and North Atlantic Oscillations is strongest during January, limited to 1965 onwards, and evident only during QBO east conditions. This has helped to constrain potential mechanisms.

6. Geomagnetic forcing is also evident in the Antarctic Oscillation. A similar temporal pattern is evident, suggesting that the onset of geomagnetic forcing of the lower atmosphere was a global event. More research into the effects of solar and geomagnetic activity in the southern hemisphere is warranted.

Chapter four continued the examination of the link between geomagnetic activity and the annular modes at daily timescales using superposed epoch analysis. It also tested for a solar-flare effect in indices of the Arctic and Antarctic Oscillations and found that:

1. There is no evidence for geomagnetic forcing of atmospheric circulation at the daily timescale. This is because geomagnetic forcing of the troposphere occurs through non-linear processes via the thermosphere and stratosphere. Accordingly, the impact of geomagnetic activity on atmospheric circulation occurs as an accumulation of subtle events and cannot be distinguished on an event-by-event basis.

2. The superposed epoch analysis method is unsuited to the examination of atmospheric data with a strong noise component and many of the published results based on this technique warrant re-evaluating.

Chapter five considered possible mechanisms and found that:

1. Geomagnetic activity influences northern hemisphere circulation via the stratospheric polar vortex and subsequently that the stratospheric changes originate in the thermosphere/mesosphere. Planetary wave activity plays an important part in linking geomagnetic activity to the troposphere. This means that the more common solar-climate mechanisms, involving cloud cover changes or ultraviolet radiative forcing, are not relevant to the geomagnetic activity forcing of recent climate change.

2. Geomagnetic activity forcing of the southern hemisphere circulation also involve stratospheric circulation (but not the polar vortex), which may originate due to ozone changes or upper atmosphere circulation.

3. Geomagnetic activity is not a proxy for solar irradiance on either monthly or daily timescales. Furthermore, the sunspot number is at best moderately (r = 0.61) correlated to solar irradiance variations at monthly timescales.

4. The relationship between geomagnetic activity and atmospheric circulation in the northern hemisphere affords some predictive ability, indicating that the relationship is strong enough to be of practical significance.

Supplementary analyses presented in chapter two and in the appendices revealed that:

1. Geomagnetic activity forcing of atmospheric circulation operates independently to other solar-climate relationships, such as the link between solar-cycle length and surface temperature and the link between the solar-cycle and stratospheric temperature. The assumptions and criticisms applicable to other solar-climate relationships cannot be automatically transferred to geomagnetic-climate relationships.

Overall, this thesis has achieved its main aim of evaluating the role that solar-modulated geomagnetic activity has played in recent climate change, and found that the impact of geomagnetic activity on the climate of the lower atmosphere cannot be ignored.

References

Abraham, S., Dhaka, S. K., Praveen, K. D., Nath, N., Nagpal, O. P., and Baluja, K. L. (1997). Lower stratosphere coupling with the mesosphere through the QBO. *Journal of Atmospheric and Solar-Terrestrial Physics* 59, 1885-1889.

Ahn, B.-H., Kroehl, H. W., Kamide, Y., and Kihn, E. A. (2000). Seasonal and solar cycle variations of the auroral electrojet indices. *Journal of Atmospheric and Solar-Terrestrial Physics* 62, 1301-1310.

Akasofu, S.-I. (1998). Aurora. *In* "From the sun: Auroras, magnetic storms, solar flares, cosmic rays." (S. T. Suess, and B. T. Tsurutani, Eds.), pp. 1-12. AGU, Washington.

Ambaum, M. H. P., Hoskins, B. J., and Stephenson, D. B. (2001). Arctic Oscillation or North Atlantic Oscillation? *Journal of Climate* 14, 3495-3507.

Andrews, D. G. (2000). "An introduction to atmospheric physics." Cambridge University Press, Cambridge. 229 pages.

Antonova, L. A., and Nusinov, A. A. (1996). On the mechanism of additional enhancement of EUV emission of solar proton flares. *Geomagnetism and Aeronomy (English Translation)* 35, 567-570.

Appenzeller, C., Weiss, A. K., and Staehelin, J. (2000). North Atlantic Oscillation modulates total ozone winter trends. *Geophysical Research Letters* 27, 1131-1134.

Arnold, N. F., and Robinson, T. R. (1998). Solar cycle changes to planetary wave propagation and their influence on the middle atmosphere circulation. *Annales Geophysicae* 16, 69-76.

Arnold, N. F., and Robinson, T. R. (2001). Solar magnetic flux influence on the dynamics of the winter middle atmosphere. *Geophysical Research Letters* 28, 2381-2384.

Ataç, T., and Özgüç, A. (1996). North-south asymmetry in the solar flare index. *Solar Physics* 166, 201-208.

Baker, D. N. (2000). Effects of the Sun on the earth's environment. *Journal of Atmospheric and Solar-Terrestrial Physics* 62, 1669-1681.

Balachandran, N. K., Rind, D., Lonergan, P., and Shindell, D. T. (1999). Effects of solar cycle variability on the lower stratosphere and the troposphere. *Journal of Geophysical Research* 104, 27321-27339.

Baldwin, M. P. (2000). The Arctic Oscillation and its role in stratosphere-troposphere coupling. *SPARC Newsletter 14*.

Baldwin, M. P., and Dunkerton, T. J. (1991). Quasi-biennial oscillation above 10 mb. *Geophysical Research Letters* 18, 1205-1208.

Baldwin, M. P., and Dunkerton, T. J. (1999). Propagation of the Arctic Oscillation from the stratosphere to the troposphere. *Journal of Geophysical Research* 104, 30937-30946.

Baldwin, M. P., and Dunkerton, T. J. (2001). Stratospheric harbingers of anomalous weather regimes. *Science* 294, 581-584.

Baldwin, M. P., Cheng, X., and Dunkerton, T. J. (1994). Observed correlations between winter-mean tropospheric and stratospheric circulation anomalies. *Geophysical Research Letters* 21, 1141-1144.

Baldwin, M. P., and Dunkerton, T. J. (1998). Quasi-biennial modulation of the southern hemisphere stratospheric polar vortex. *Geophysical Research Letters* 25, 3343-3346.

Baliunas, S., and Soon, W. (1995). Are variations in the length of the activity cycle related to changes in brightness in solar-type stars? *The Astrophysical Journal* 450, 896-901.

Barnett, T. P. (1989). A solar-ocean relation: fact or fiction? *Geophysical Research Letters* 16, 803-806.

Bazilevskaya, G. A., Krainev, M. B., and Makhmutov, V. S. (2000). Effects of cosmic rays on the earth's environment. *Journal of Atmospheric and Solar-Terrestrial Physics* 62, 1577-1586.

Beer, J., Tobias, S., and Weiss, N. (1998). An active sun throughout the Maunder Minimum. *Solar Physics* 181, 237-249.

Belikov, Y. (2000). Dependence of solar radiation in the polar stratosphere on the distribution of ozone and stratospheric aerosol. *Physics and Chemistry of the Earth (B)* 25, 423-426.

Bell, J.T., Gussenhoven, M.S., and Mullen, E.G. (1997). Super storms. *Journal of Geophysical Research* 102, 14189-14198.

Belov, A. V., Eroshenko, E. A., Oleneva, V. A., Struminsjky, A. B., and Yanke, V. G. (2001). What determines the magnitude of Forbush decreases? *Advances in Space Research* 27, 625-630.

Benzi, R., Parisi, G., Sutera, A., and Vulpiani, A. (1982). Stochastic resonance in climate change. *Tellus* 34, 10-16.

Besprozvannaya, A. S., Ohl, G. I., Sazonov, B. I., Scherba, I. A., Schuka, T. I., and Troshichev, O. A. (1997). Influence of short-term changes in solar activity on baric field perturbations in the stratosphere. *Journal of Atmospheric and Solar-Terrestrial Physics* 59, 1233-1244.

Black, R. X. (2002). Stratospheric forcing of surface climate in the Arctic Oscillation. *Journal of Climate* 15, 268-277.

Bochníček, J., Bucha, V., Hejda, P., and Pýcha, J. (1996). Relation between Northern Hemisphere winter temperatures and geomagnetic or solar activity at different QBO phases. *Journal of Atmospheric and Terrestrial Physics* 58, 883-897.

Bochníček, J., Hejda, P., Bucha, V., and Pýcha, J. (1999). Possible geomagnetic activity effects on weather. *Annales Geophysicae* 17, 925-932.

Bogdanov, N. N., and Leont'yev, S. V. (1991). Vertical winds in the upper latitude thermosphere. *Geomagnetism and Aeronomy* 31, 889-891.

Brooks, C. E. P. (1934). The variation of the annual frequency of thunderstorms in relation to sunspots. *Quarterly Journal of the Royal Meteorological Society* 60, 153-165.

Brougham, H. (1803). Herschel on the new planets. *Edinburgh Review* 1, 426-431.

Bucha, V. (1991). Solar and geomagnetic variability and changes of weather and climate. *Journal of Atmospheric and Terrestrial Physics* 53, 1161-1172.

Bucha, V. (2002). Long-term trends in geomagnetic and climatic variability. *Physics and Chemistry of the Earth* 27, 427-431.

Bucha, V., and Bucha, V. (1998). Geomagnetic forcing of changes in climate and in the atmospheric circulation. *Journal of Atmospheric and Solar-Terrestrial Physics* 60, 145-169.

Bucha, V., and Bucha, V. (2002). Geomagnetic forcing and climate variations in Europe, North America and in the Pacific Ocean. *Quaternary International* 91, 5-15.

Burns, G. B., Bond, F. R., and Cole, K. D. (1980). An investigation of the southern hemisphere vorticity response to solar sector boundary crossing. *Journal of Atmospheric and Terrestrial Physics* 42, 765-769.

Butler, C. J. (1994). Maximum and minimum temperatures at Armagh Observatory, 1844-1992, and the length of the sunspot cycle. *Solar physics* 152, 35-42.

Callis, L. B., Natarajan, M., and Lambeth, J. D. (2001). Solar-atmospheric coupling by electrons (SOLACE) 3. Comparisons of simulations and observations, 1979-1997, issues and implications. *Journal of Geophysical Research* 106, 7523-7539.

Callis, L. B., Natarajan, M., Evans, D. S., and Lambeth, J. D. (1998a). Solar atmospheric coupling by electrons (SOLACE) 1. Effects of the May 12, 1997 solar event on the middle atmosphere. *Journal of Geophysical Research* 103, 28405-28419.

Callis, L. B., Natarajan, M., Lambeth, J. D., and Baker, D. (1998b). Solar atmospheric coupling by electrons (SOLACE). *Journal of Geophysical Research* 103, 28241-28438.

Cane, H. V. (2000). Coronal mass ejections and Forbush decreases. *Space Science Reviews* 93, 55-77.

Castagnoli, G. C., Bernasconi, S. M., Bonino, G., Monica, P. D., and Taricco, C. (1999). 700 year record of the 11 year solar cycle by planktonic foraminifera of a shallow water Mediterranean core. *Advances in Space Research* 24, 233-236.

Cavalieri, D. J., and Häkkinen, S. (2001). Arctic climate and atmospheric planetary waves. *Geophysical Research Letters* 28, 791-794.

Chandra, S., Ziemke, J. R., and Stewart, R. W. (1999). An 11-year solar cycle in tropospheric ozone from TOMS measurement. *Geophysical Research Letters* 26, 185-188.

Chang, C.-P., Harr, P., and Ju, J. (2001). Possible roles of Atlantic circulations on the weakening Indian Monsoon rainfall-ENSO relationship. *Journal of Climate* 14, 2376-2380.

Chen, J. (1997). Prominence eruptions and geoeffective solar wind structures. *In* "Magnetic Storms." (B. T. Tsurutani, W. D. Gonzalez, Y. Kamide, and J. K. Arballo, Eds.), pp. 45-57. American Geophysical Union, Washington.

Chree, C. (1913). Some phenomena of sunspots and of terrestrial magnetism at Kew Observatory. *Philosophical transactions of the Royal Society of London. Series A.*212, 75-116.

Christiansen, B. (2001). Downward propagation of zonal mean zonal wind anomalies from the stratosphere to the troposphere: Model and reanalysis. *Journal of Geophysical Research* 106, 27307-27322.

Christiansen, B. (2002). On the physical nature of the Arctic Oscillation. *Geophysical Research Letters* 29, 10.1029/2002GL015208.

Clilverd, M. A., Clark, T. D. G., Clarke, E., and Rishbeth, H. (1998). Increased magnetic storm activity from 1868 to 1995. *Journal of Atmospheric and Solar-Terrestrial Physics* 60, 1047-1056.

Cliver, E. W. (1994). Solar activity and geomagnetic storms: the first 40 years. *Eos, Transactions* 75, 569, 574-575.

Cliver, E. W., Boriakoff, V., and Feynman, J. (1998). Solar variability and climate change: Geomagnetic aa index and global surface temperature. *Geophysical Research Letters* 25, 1035-1038.

Cliver, E. W., Kamide, Y., and Ling, A. G. (2002). The semiannual variation of geomagnetic activity: phases and profiles for 130 years of aa data. *Journal of Atmospheric and Solar-Terrestrial Physics* 64, 47-53.

Clúa de Gonzalez, A. L., Gonzalez, W. D., Dutra, S. L. G., and Tsurutani, B. (1993). Periodic variation in the geomagnetic activity: A study based on the Ap index. *Journal of Geophysical Research* 98, 9215-9231.

Clúa de Gonzalez, A. L., Silbergleit, V. M., Gonzalez, W. D., and Tsurutani, B. T. (2001). Annual variation of geomagnetic activity. *Journal of Atmospheric and Solar-Terrestrial Physics* 63, 367-374.

Currie, R. G. (1974). Solar cycle signal in surface air temperature. *Journal of Geophysical Research* 79, 5657-5660.

Currie, R. G. (1996). M_n and S_c signal in North Atlantic tropical cyclone occurrence. *International Journal of Climatology* 16, 427-439.

Currie, R. G., and Vines, R. G. (1996). Evidence for luni-solar M_n and solar cycle S_c signals in Australian rainfall data. *International Journal of Climatology* 16, 123-1265.

Damon, P. E., and Peristykh, A. N. (1999). Solar cycle length and 20th century northern hemisphere warming: revisited. *Geophysical Research Letters* 26, 2469-2472.

Danilov, A. D., and Laštovička, J. (2001). Effects of geomagnetic storms on the ionosphere and atmosphere. *International Journal of Geomagnetism and Aeronomy* 2, 1-16.

Davies, R. (1993). Increased transmission of ultraviolet radiation to the surface due to stratospheric scattering. *Journal of Geophysical Research* 98, 7251-7253.

Davydova, Y. I., and Davydov, V. V. (1996). Solar periods and meteorological parameters of the earth's atmosphere. *Geomagnetism and Aeronomy (English Translation)* 35, 857-859.

Dessler, A. J. (1975). Some problems in coupling solar activity to meteorological phenomena. *Goddard Space Flight Center Special Report* NASA SP-366, 299-310.

Detwiler, A. (1993). Comment on "Apparent tropospheric response to MeV-GeV particle flux variation: A connection via electrofreezing of supercooled water in high-level clouds?" by Brian A. Tinsley and Glen W. Deen. *Journal of Geophysical Research* 98, 16887-16888.

Dewan, E. M., and Shapiro, R. (1991). Are sunspot-weather correlations real? *Journal of Atmospheric and Terrestrial Physics* 53, 171-174.

Dickinson, R. E. (1975). Solar variability and the lower atmosphere. *Bulletin of the American Meteorological Society* 56, 1240-1248.

Dong, B.-W., Sutton, R. T., Jewson, S. P., O'Neill, A., and Slingo, J. M. (2000). Predictable winter climate in the North Atlantic sector during the 1997-1999 ENSO cycle. *Geophysical Research Letters* 27, 985-988.

Douglass, A. E. (1909). Weather cycles in the growth of big trees. *Monthly Weather Review* 37, 225-237.

Eddy, J. A. (1976). The Maunder Minimum. *Science* 192, 1189-1202.

Eddy, J. A. (1977). Climate and the changing sun. *Climatic Change* 1, 173-190.

Egorova, L. V., Vovk, V. Y., and Troshichev, O. A. (2000). Influence of variations of the cosmic rays on atmospheric pressure and temperature in the Southern geomagnetic pole region. *Journal of Atmospheric and Solar-Terrestrial Physics* 62, 955-966.

Elsner, J. B., and Kavlakov, S. P. (2001). Hurricane intensity changes associated with geomagnetic variation. *Atmospheric Science Letters* doi:10.1006/ asle.2001.0040.

Engebretson, M. J., and Maueresberge, K. (1983). The response of thermospheric atomic nitrogen to magnetic storms. *Journal of Geophysical Research* 88, 6331-6338.

Engfer, D. W., and Tinsley, B. A. (1999). An investigation of short-term solar wind modulation of atmospheric electricity at Mauna Loa Observatory. *Journal of Atmospheric and Solar-Terrestrial Physics* 61, 943-953.

Fedulina, I., and Laštovička, J. (2001). Effect of Forbush Decreases of cosmic ray flux on ozone at higher middle latitudes. *Advances in Space Research* 27, 2003-2006.

Feldstein, S. B. (2000). The timescale, power spectra, and climate noise properties of teleconnection patterns. *Journal of Climate* 13, 4430-4440.

Feldstein, S. B. (2002). The recent trend and variance increase of the annular mode. *Journal of Climate* 15, 88-94.

Fligge, M., Solanki, S. K., and Beer, J. (1999). Determination of solar cycle length variations using the continuous wavelet transform. *Astronomy and Astrophysics* 346, 313-321.

Forbes, J. M., Gonzalez, R., Marcos, F. A., Revelle, D., and Parish, H. (1996). Magnetic storm response of lower thermosphere density. *Journal of Geophysical Research* 101, 2313-2319.

Forbush, S. E. (1954). World-wide cosmic-ray variations, 1937-1952. *Journal of Geophysical Research* 59, 525-542.

Forbush, S. E. (1958). Cosmic-ray intensity variations during two solar cycles. *Journal of Geophysical Research* 63, 651-669.

Foukal, P. (1998). Solar irradiance variations and climate. *In* “From the sun: Auroras, magnetic storms, solar flares, cosmic rays.” (S. T. Suess, and B. T. Tsurutani, Eds.), pp. 103-112. AGU, Washington.

Friis-Christensen, E. (1993). Solar activity variations and global temperature. *Energy* 18, 1273-1284.

Friis-Christensen, E., and Lassen, K. (1991). Length of the solar cycle: an indicator of solar activity closely associated with climate. *Science* 254, 698-700.

Friis-Christensen, E., and Svensmark, H. (1997). What do we really know about the sun-climate connection? *Advances in Space Research* 20, 913-921.

Friis-Christensen, E. (2000). Sun, clouds and climate – an editorial comment. *Climatic Change* 47, 1-5.

Fröhlich, C., and Lean, J. (1998). The sun's total irradiance: cycles, trends and related climate change uncertainties since 1976. *Geophysical Research Letters* 25, 4377-4380.

Fuller-Rowell, T. J., Codrescu, M. V., Moffett, R. J., and Quegan, S. (1994). Response of the thermosphere and ionosphere to geomagnetic storms. *Journal of Geophysical Research* 99, 3893-3914.

Fuller-Rowell, T. J., Codrescu, M. V., Roble, R. G., and Richmond, A. D. (1997). How does the thermosphere and ionosphere react to a geomagnetic storm? *In* "Magnetic storms." (B. T. Tsurutani, W. D. Gonzalez, Y. Kamide, and J. K. Arballo, Eds.), pp. 203-225. American Geophysical Union, Washington.

Gabis, I. P., and Troshichev, O. A. (2000). Influence of short-term changes in solar activity on baric field perturbations in the stratosphere and troposphere. *Journal of Atmospheric and Solar-Terrestrial Physics* 62, 725-735.

Gammaitoni, L., Hänggi, P., Jung, P., and Marchesoni, F. (1998). Stochastic resonance. *Reviews of Modern Physics* 70, 223-287.

Geller, M. A., and Alpert, J. C. (1980). Planetary wave coupling between the troposphere and the middle atmosphere of a possible sun-weather mechanism. *Journal of the Atmospheric Sciences* 37, 1197-1215.

George, S. E., and Saunders, M. A. (2001). North Atlantic Oscillation impact on tropical north Atlantic winter atmospheric variability. *Geophysical Research Letters* 28, 1015-1018.

Gillett, N. P., Hegerl, G. C., Allen, M. R., and Stott, P. A. (2000). Implication of changes in the northern hemisphere circulation for the detection of anthropogenic climate change. *Geophysical Research Letters* 27, 993-996.

Goldstein, B. E. (1998). The solar wind. *In* "From the sun: Auroras, magnetic storms, solar flares, cosmic rays." (S. T. Suess, and B. T. Tsurutani, Eds.), pp. 81-90. AGU, Washington.

Gong, D., and Wang, S. (1999). Definition of Antarctic oscillation index. *Geophysical Research Letters* 26, 459-462.

Gonzalez, W. D., Joselyn, J. A., Kamide, Y., Kroehl, H. W., Rostoker, G., Tsurutani, B. T., and Vasyliunas, V. M. (1994). What is a geomagnetic storm? *Journal of Geophysical Research* 99, 5771-5792.

Gosling, J. T., McComas, D. J., Phillips, J. L., and Bame, S. J. (1991). Geomagnetic activity associated with earth passage of interplanetary shock disturbances and coronal mass ejections. *Journal of Geophysical Research* 96, 7831-7839.

Greatbatch, R. J. (2000). The North Atlantic Oscillation. *Stochastic Environmental Research and Risk Assessment* 14, 213-242.

Gribbin, J. (1987). Magnetic pointers to stormy weather. *New Scientist* January, 70-72.

Groveman, B. S., and Landsberg, H. E. (1979). Simulated northern hemisphere temperature departures 1579-1880. *Geophysical Research Letters* 6, 767-769.

Haigh, J. D. (1996). The impact of solar variability on climate. *Science* 272, 981-984.

Haigh, J. D. (1999). Modelling the impact of solar variability on climate. *Journal of Atmospheric and Solar-Terrestrial Physics* 61, 63-72.

Haigh, J. D. (2001). Climate variability and the influence of the sun. *Science* 294, 2109-2111.

Hallahan, M., and Rosenthal, R. (1996). Statistical power: concepts, procedures, and applications. *Behaviour Research and Therapy* 34, 489-499.

Hameed, S., and Gong, G. (1994). Variation of spring climate in lower-middle Yangtse river valley and its relation with solar-cycle length. *Geophysical Research Letters* 21, 2693-2696.

Hartley, D. E., Villarin, J. T., Black, R. X., and Davis, C. A. (1998). A new perspective on the dynamical link between the stratosphere and troposphere. *Nature* 391, 471-474.

Hartmann, D. L., and Lo, F. (1998). Wave-driven zonal flow vacillation in the Southern Hemisphere. *Journal of the Atmospheric Sciences* 55, 1303-1315.

Hartmann, D. L., Wallace, J. M., Limpasuvan, V., Thompson, D. W. J., and Holton, J. R. (2000). Can ozone depletion and global warming interact to produce rapid climate change? *Proceedings of the National Academy of Science* 97, 1412-1417.

Hathaway, D. H. (1998). The solar dynamo. *In* "From the sun: Auroras, magnetic storms, solar flares, cosmic rays." (S. T. Suess, and B. T. Tsurutani, Eds.), pp. 113-122. AGU, Washington.

Haurwitz, M. W., and Brier, G. W. (1981). A critique of the superposed epoch analysis method: its application to solar-weather relations. *Monthly Weather Review* 109, 2074-2079.

Herschel, W. (1801). Observations tending to investigate the nature of the sun, in order to find the causes or symptoms of its variable emission of light and heat; with remarks on the use that may be possibly drawn from solar observations. *Philosophical Transactions of the Royal Society (London)* Part 1, 265-318.

Hilmer, M., and Jung, T. (2000). Evidence for a recent change in the link between the North Atlantic Oscillation and Arctic sea ice export. *Geophysical Research Letters* 27, 989-992.

Hodell, D. A., Brenner, M., Curtis, J. H., and Guilderson, T. (2001). Solar forcing of drought frequency in the Maya lowlands. *Science* 292, 1367-1370.

Holton, J. R., and Tan, H.-C. (1980). The influence of the equatorial quasi-biennial oscillation on the global circulation at 50 mb. *Journal of the Atmospheric Sciences* 37, 2200-2208.

Hood, L. L. (1997). The solar cycle variation of total ozone: Dynamical forcing in the lower stratosphere. *Journal of Geophysical Research* 102, 1355-1370.

Hood, L. L. (1999). Effect of short-term solar UV variability on the stratosphere. *Journal of Atmospheric and Solar-Terrestrial Physics* 61, 45-51.

Hopgood, P. A., and Barton, C. E. (1987). The great magnetic storm of February 1986. *Search* 18, 26-30.

Hoyt, D. V., and Schatten, K. H. (1993). A discussion of plausible solar irradiance variations, 1700-1992. *Journal of Geophysical Research* 98A, 18895-18906.

Hudson, H. S. (1997). Solar antecedents of geomagnetic storms. *In* "Magnetic storms." (B. T. Tsurutani, W. D. Gonzalez, Y. Kamide, and J. K. Arballo, Eds.), pp. 35-43. American Geophysical Union, Washington.

Huesmann, A. S., and Hitchman, M. H. (2001). The stratospheric quasi-biennial oscillation in the NCEP reanalyses: climatological structures. *Journal of Geophysical Research* 106, 11859-11874.

Hurrell, J. W. (1995). Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. *Science* 269, 676-679.

Hurrell, J. W. (1996). Influence of variations in extratropical wintertime teleconnections on northern hemisphere temperature. *Geophysical Research Letters* 23, 665-668.

Hurrell, J. W., and van Loon, H. (1997). Decadal variations in climate associated with the North Atlantic Oscillation. *Climatic Change* 36, 301-326.

Inclán, C., and Tiao, G. C. (1994). Use of cumulative sums of squares for retrospective detection of changes of variance. *Journal of the American Statistical Association* 89, 913-923.

Jackman, C. H., Fleming, E. L., Vitt, F. M., and Considine, D. B. (1999). The influence of solar proton events on the ozone layer. *Advances in Space Research* 24, 625-630.

Jacobeit, J., Jönsson, P., Bärring, L., Beck, C., and Ekström, M. (2000). Zonal indices for Europe 1780-1995 and running correlations with temperature. *Climatic Change* 8, 219-241.

Jacobi, C., and Beckmann, B.-R. (1999). On the connection between upper atmospheric dynamics and tropospheric parameters: correlations between mesopause region winds and the North Atlantic Oscillation. *Climatic Change* 43, 629-643.

Jokipii, J. R. (1998). Cosmic Rays. *In* "From the sun: Auroras, magnetic storms, solar flares, cosmic rays." (S. T. Suess, and B. T. Tsurutani, Eds.), pp. 123-132. AGU, Washington.

Jones, J. W., Hansen, J. W., Royce, F. S., and Messina, C. D. (2000). Potential benefits of climate forecasting to agriculture. *Agriculture ecosystems and environment* 82, 169-184.

Jones, P. D., Parker, D. E., Osborn, T. J., and Briffa, K. R. (2001). Global and hemispheric temperature anomalies – land and marine instrumental records. *Trends: a compendium of data on global change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.*

Jørgensen, T. S., and Hansen, A. K. (2000). Comments on "Variation of cosmic ray flux and global cloud coverage – a missing link in solar-climate relationships" by Henrik Svensmark and Eigil Friis-Christensen [Journal of Atmospheric and Solar Terrestrial Physics 59 (1997) 1225-1232]. *Journal of Atmospheric and Solar-Terrestrial Physics* 62, 73-77.

Joselyn, J. A. (1998). The human impact of solar flares and magnetic storms. *In* "From the sun: Auroras, magnetic storms, solar flares, cosmic rays." (S. T. Suess, and B. T. Tsurutani, Eds.), pp. 67-72. AGU, Washington.

Joselyn, J. A., Anderson, J., Coffey, H., Harvey, K., Hathaway, D., Heckman, G., Hildner, E., Mende, W., Schatten, K., Thompson, R., Thompson, A. W. P., and White, O. R. (1996). Solar Cycle 23 Project: Summary of panel findings. *http://www.sec.noaa.gov/info/Cycle23.html*.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Repelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R., and Jospeh, D. (1996). The *NCEP/NCAR* 40-year reanalysis project. *Bulletin of the American Meteorological Society* 77, 437-471.

Kane, R. P. (1995). Quasi-biennial oscillation in ionospheric parameters measured at Juliusruh (55°N, 13°E). *Journal of Atmospheric and Terrestrial Physics* 57, 415-419.

Karinen, A., Mursula, K., Ulich, T., and Manninen, J. (2002). Does the magnetosphere behave differently on weekends? *Annales Geophysicae* 20, 1137-1142.

Keller, C. F. (1999). Climate, modeling, and predictability. *Physica D* 133, 296-308.

Kelly, P. M., and Wigley, T. M. L. (1992). Solar cycle length variations, greenhouse forcing and global climate. *Nature* 360, 328-330.

Kernthaler, S. C., Toumi, R., and Haigh, J. D. (1999). Some doubts concerning a link between cosmic ray fluxes and global cloudiness. *Geophysical Research Letters* 26, 863-865.

Kerr, R. A. (1999). A new force in high-latitude climate. *Science* 284, 241-242.

Kirkland, M. W., Tinsley, B. A., and Hoeksema, J. T. (1996). Are stratospheric aerosols the missing link between tropospheric vorticity and earth transits of the heliospheric current sheet? *Journal of Geophysical Research* 101, 29689-29699.

Knox, J. L., Higuchi, K., Shabbar, A., and Sargent, N. E. (1988). Secular variation of northern hemisphere 50 kPa geopotential height. *Journal of Climate* 1, 500-511.

Kodera, K. (1991). The solar and equatorial QBO influence on the stratospheric circulation during the early northern-hemisphere winter. *Geophysical Research Letters* 18, 1023-1026.

Kodera, K., and Chiba, M. (1995). Tropospheric circulation changes associated with stratospheric sudden warmings: A case study. *Journal of Geophysical Research* 100, 11055-11068.

Kodera, K., and Yamazaki, K. (1994). A possible influence of recent polar stratospheric coolings on the troposphere in the northern hemisphere winter. *Geophysical Research Letters* 21, 809-812.

Kodera, K., Chiba, M., and Shibata, K. (1991). A general circulation model study of the solar and QBO modulation of the stratospheric circulation during the northern hemisphere winter. *Geophysical Research Letters* 18, 1209-1212.

Kodera, K., Koide, H., and Yoshimura, H. (1999). Northern Hemisphere winter circulation associated with the North Atlantic Oscillation and stratospheric polar-night jet. *Geophysical Research Letters* 26, 443-446.

Kodera, K., Kuroda, Y., and Pawson, S. (2000). Stratospheric sudden warmings and slowly propagating zonal-mean zonal wind anomalies. *Journal of Geophysical Research* 105, 12351-12359.

Kodera, K., Yamazaki, K., Chiba, M., and Shibata, K. (1990). Downward propagation of upper stratospheric mean zonal wind perturbation to the troposphere. *Geophysical Research Letters* 17, 1263-1266.

Kohsiek, A., Glassmeier, K. H., and Hirooka, T. (1995). Periods of planetary waves in geomagnetic variations. *Annales Geophysicae* 13, 168-176.

Kristjánsson, J. E., and Kristiansen, J. (2000). Is there a cosmic ray signal in recent variations in global cloudiness and cloud radiative forcing? *Journal of Geophysical Research* 105, 11851-11863.

Krivolutsky, A. A. (2001). Cosmic ray influence on chemical composition of the atmosphere of the earth. *Advances in Space Research* 27, 1993-2002.

Krivolutsky, A. A., Bazilevskaya, G. A., Vyushkova, T. Y., and Knyazeva, G. V. (2001). Long-term tropospheric variations of ozone content caused by galactic cosmic ray influence. *Advances in Space Research* 27, 2019-2024.

Krivolutsky, A., Bazilevskaya, G., Vyushkova, T., and Knyazeva, G. (2002). Influence of cosmic rays on chemical composition of the atmosphere: data analysis and photochemical modelling. *Physics and Chemistry of the Earth* 27, 471-476.

Krzyścin, J. W. (1995). Interannual fluctuations of the stratospheric temperature over the north polar region. *Journal of Atmospheric and Terrestrial Physics* 57, 375-382.

Labitzke, K. (1987). Sunspots, the QBO, and the stratospheric temperature in the north polar region. *Geophysical Research Letters* 14, 535-537.

Labitzke, K. (2001). The global signal of the 11-year sunspot cycle in the stratosphere: Differences between solar maxima and minima. *Meteorologische Zeitschrift* 10, 83-90.

Labitzke, K., and van Loon, H. (1988). Associations between the 11-year solar cycle, the QBO and the atmosphere. Part I: the troposphere and stratosphere in the northern hemisphere winter. *Journal of Atmospheric and Terrestrial Physics* 50, 197-206.

Labitzke, K., and van Loon, H. (1993). Some recent studies of probable connections between solar and atmospheric variability. *Annales Geophysicae* 11, 1084-1094.

Labitzke, K., and van Loon, H. (1996). The solar signal in the north polar VORTEX in January-February – a brief review for an aspect of STEP working group V. *Journal of Geomagnetism and Geoelectricity* 48, 161-164.

Labitzke, K., and van Loon, H. (1997). The signal of the 11-year sunspot cycle in the upper troposphere-lower stratosphere. *Space Science Reviews* 80, 393-410.

Labitzke, K., and van Loon, H. (2000). The QBO effect on the solar signal in the global stratosphere in the winter of the Northern Hemisphere. *Journal of Atmospheric and Solar-Terrestrial Physics* 62, 621-628.

Lam, H.-L., and Samson, J. C. (1994). An investigation of the time-delay between solar events and geomagnetic disturbances using a new method of superposed epoch analysis. *Journal of Geomagnetism and Geoelectricity* 46, 107-113.

Landi, R., Moreno, G., Storini, M., and Antalová, A. (1998). Coronal mass ejections, flares, and geomagnetic storms. *Journal of Geophysical Research* 103, 20553-20559.

Lang, K. R. (2001). "The Cambridge encyclopedia of the sun." Cambridge University Press, Cambridge. 256 pages.

Lassen, K., and Friis-Christensen, E. (2000). Solar cycle lengths and climate: a reference revisited – reply. *Journal of Geophysical Research* 105, 27,493-27,495.

Lassen, K., and Friis-Christensen, E. F. (1995). Variability of the solar cycle length during the past five centuries and the apparent association with terrestrial climate. *Journal of Atmospheric and Terrestrial Physics* 57, 835-845.

Laštovička, J. (1990). The response of the lower ionosphere, stratospheric ozone, and the vorticity area index in the troposphere to geomagnetic storms. *Geomagnetic and Aeronomy* 30, 380-383.

Laštovička, J. (1996). Effects of geomagnetic storms in the lower ionosphere, middle atmosphere and troposphere. *Journal of Atmospheric and Solar Terrestrial Physics* 58, 831-843.

Laštovička, J., and Mlch, P. (1999). Is ozone affected by geomagnetic storms? *Advances in Space Research* 24, 671.

Lauroesch, T. J., Edinger, J. R., and Lauroesch, J. T. (1996). Full moon and empty skies? *International Journal of Climatology* 16, 113-117.

Laut, P., and Gunderman, J. (1998a). Does the correlation between solar cycle lengths and northern hemisphere land temperatures rule out any significant global warming from greenhouse gases? *Journal of Atmospheric and Solar-Terrestrial Physics* 60, 1-3.

Laut, P., and Gunderman, J. (1998b). Solar cycle length hypothesis appears to support the IPCC on global warming. *Journal of Atmospheric and Solar-Terrestrial Physics* 60, 1719-1728.

Laut, P., and Gundermann, J. (2000). Solar cycle lengths and climate: a reference revisited. *Journal of Geophysical Research* 105, 27489-27492.

Lawrence, J. K., and Ruzmaikin, A. A. (1998). Transient solar influence on terrestrial temperature fluctuations. *Geophysical Research Letters* 25, 159-162.

Lean, J. (2000). Evolution of the sun's spectral irradiance since the Maunder Minimum. *Geophysical Research Letters* 27, 2425-2428.

Lean, J., and Rind, D. (1999). Evaluating sun-climate relationships since the Little Ice Age. *Journal of Atmospheric and Solar-Terrestrial Physics* 61, 25-36.

Lean, J., Beer, J., and Bradley, R. (1995). Reconstruction of solar irradiance since 1610: Implications for climate change. *Geophysical Research Letters* 22, 3195-3198.

Lean, J., Livingston, W., Skumanich, A., and White, O. (1992). Estimating the sun's radiative output during the Maunder Minimum. *Geophysical Research Letters* 19, 1591-1594.

Lin, R. P. (1998). Solar flare particles. *In* "From the sun: Auroras, magnetic storms, solar flares, cosmic rays." (S. T. Suess, and B. T. Tsurutani, Eds.), pp. 91-102. AGU, Washington.

Lockwood, M. (2001). Long-term variations in the magnetic fields of the sun and the heliosphere: their origin, effects, and implications. *Journal of Geophysical Research* 106, 16021-16038.

Lockwood, M., Stamper, R., and Wild, M. N. (1999). A doubling of the sun's coronal magnetic field during the past 100 years. *Nature* 399, 437-439.

Lohmann, U., and Feichter, J. (2001). Can the direct and semi-direct aerosol effect compete with the indirect effect on a global scale? *Geophysical Research Letters* 28, 159-161.

Lu, G., Baker, D. N., McPherron, R. L., Farrugia, C. J., Lummerzheim, D., Ruohoniemi, J. M., Rich, F. J., Evans, D. S., Lepping, R. P., Brittnacher, M., Li, X., Greenwald, R., Sofko, G., Villain, J., Lester, M., Thayer, J., Moretto, T., Milling, D., Troshichev, O., Zaitzev, A., Odintzov, V., Makarov, G., and Hayashi, K. (1998). Global energy deposition during the January 1997 magnetic cloud event. *Journal of Geophysical Research* 103, 11685-11694.

Lu, Q.-B., and Sanche, L. (2001). Effects of cosmic rays on atmospheric chlorofluorocarbon dissociation and ozone depletion. *Physical Review Letters* 87, 78,501-78,504.

Lundstedt, H. (1984). Influence of interplanetary interaction regions on geomagnetic disturbances and tropospheric circulation. *Planetary and Space Scienec* 32, 1541-1545.

Lundstedt, H. (1996). Solar origin of geomagnetic storms and predictions. *Journal of Atmospheric and Terrestrial Physics* 58, 821-830.

Lyons, L. R. (2000). Geomagnetic disturbances: characteristics of, distinction between types, and relations to interplanetary conditions. *Journal of Atmospheric and Solar-Terrestrial Physics* 62, 1087-1114.

MacDonald, N. J., and Roberts, W. O. (1960). Further evidence of a solar corpuscular influence on large-scale circulation at 300 mb. *Journal of Geophysical Research* 65, 529-534.

MacDonald, N. J., and Woodbridge, D. D. (1959). Relation of geomagnetic disturbances to circulation changes at 30,000-foot level. *Science* 129, 638-639.

Makarova, L. N., and Shirochkov, A. V. (2001). Impact of the solar wind dynamics on the ozone density variations. *Advances in Space Research* 27, 2013-2018.

Mann, M. E., Bradley, R. S., and Hughes, M. K. (1998). Global-scale temperature patterns and climate forcing over the past six centuries. *Nature* 392, 779-787.

Marcucci, M. F., Orsini, S., Candidi, M., and Storini, M. (1999). Auroral activity and Antarctic stratospheric ozone. *Physics and Chemistry of the Earth (C)* 24, 141-146.

Marcus, S. L., Ghil, M., and Ide, K. (1999). Models of solar irradiance variability and the instrumental temperature record. *Geophysical Research Letters* 26, 1449-1452.

Märcz, F. (1990). Atmospheric electricity and the 11 year solar cycle associated with QBO. *Annales Geophysicae* 8, 525-530

Marquardt, C., and Naujokat, B. (1997). An update of the equatorial QBO and its variability. *1st SPARC Gen. Assemb., Melbourne Australia, WMO/TD-No. 814* 1, 87-90.

Marshall, J., Johnson, H., and Goodman, J. (2001). A study of the interaction of the North Atlantic Oscillation with ocean circulation. *Journal of Climate* 14, 1399-1421.

Mayaud, P.-N. (1972). The aa indices: A 100-year series characterizing the magnetic activity. *Journal of Geophysical Research* 77, 6870-6874.

McNamara, B., and Wiesenfeld, K. (1989). Theory of stochastic resonance. *Physical Review A* 39, 4854-4868.

Mendoza, B., Lara, A., Maravilla, D., and Jáuregui, E. (2001). Temperature variability in central Mexico and its possible association to solar activity. *Journal of Atmospheric and Solar-Terrestrial Physics* 63, 1891-1900.

Mohnen, V. A. (1990). Stratospheric ion and aerosol chemistry and possible links with cirrus cloud microphysics – a critical assessment. *Journal of the Atmospheric Sciences* 47, 1933-1948.

Moritz, R. E., Bitz, C. M., and Steig, E. J. (2002). Dynamics of recent climate change in the Arctic. *Science* 297, 1497-1502.

Motulsky, H. (1995). “Intuitive biostatistics.” Oxford University Press, New York. 408 pages.

Mursula, K., and Ulich, T. (1998). A new method to determine the solar cycle length. *Geophysical Research Letters* 25, 1837-1840.

NASA Workshop on Sun-Climate Connections: summary report. Sprigg, W. A. (Convener). March 6-8 (2000) University of Arizona, Tuscon.

Naujokat, B. (1986). An update of the observed quasi-biennial oscillation of the stratospheric winds over the tropics. *Journal of Atmospheric Science* 43, 1873-1877.

Ney, E. P. (1959). Cosmic radiation and the weather. *Nature* 183, 451-452.

Nicholls, N. (2001). The insignificance of significance testing. *Bulletin of the American Meteorological Society*.

Norris, J. R. (1999). On trends and possible artifacts in global ocean cover between 1952 and 1995. *Journal of Climate* 12.

Ogallo, L. A., Boulahya, M. S., and Keane, T. (2000). Applications of seasonal to interannual climate prediction in agricultural planning and operations. *Agricultural and Forest Meteorology* 103, 159-166.

Olsen, N., and Kiefer, M. (1995). Geomagnetic daily variations produced by a QBO in thermospheric prevailing winds. *Journal of Atmospheric and Terrestrial Physics* 57, 1583-1589.

O'Sullivan, P.E., Moyeed, R., Cooper, M.C., and Nicholson, M.J. (2002). Comparison between instrumental, observational and high resolution proxy sedimentary records of Late Holocene climatic change – a discussion of possibilities. *Quaternary International* 88, 27-44.

Pang, K. D., and Yau, K. K. (2002). Ancient observations link changes in sun's brightness and earth's climate. *Eos* 83, 481 and 489-490.

Perlwitz, J., and Graf, H.-F. (1995). The statistical connection between tropospheric and stratospheric circulation of the northern hemisphere in winter. *Journal of Climate* 8, 2281-2295.

Perlwitz, J., Graf, H.-F., and Voss, R. (2000). The leading variability mode of the coupled troposphere-stratosphere winter circulation in different climate regimes. *Journal of Geophysical Research* 105, 6915-6926.

Perry, A. (2000). The North Atlantic Oscillation: an enigmatic see-saw. *Progress in Physical Geography* 24, 289-294.

Peterson, T. C., and Vose, R. C. (1997). An overview of the Global Historical Climatology Network database. *Bulletin of the American Meteorological Society* 78, 2837-2849.

Pirjola, R., Viljanen, A., Pulkkinen, A., and Amm, O. (2000). Space weather risk in power systems and pipelines. *Physics and Chemistry of the Earth (C)* 25, 333-337.

Pittock , B. A. (1983). Solar variability, weather and climate: an update. *Quarterly Journal of the Royal Meteorological Society* 109, 23-55.

Pittock, A. B. (1978). A critical look at long-term sun-weather relationships. *Reviews of Geophysics and Space Physics* 16, 400-420.

Pittock, A. B. (1979). Solar cycles and the weather: successful experiments in autosuggestion? *In* "Solar-terrestrial influences on weather and climate." (B. M. McCormac, and T. A. Seliga, Eds.), pp. 181-192. D. Reidel Publishing Company, Dordrecht.

Prölss, G. W., and Roemer, M. (2000). Heating of the polar upper atmosphere. *Physics and Chemistry of the Earth (C)* 25, 547-549.

Pudovkin, M. I., and Babushkina, S. V. (1992a). Influences of solar flares and disturbances of the interplanetary medium on the atmospheric circulation. *Journal of Atmospheric and Terrestrial Physics* 54, 841-846.

Pudovkin, M. I., and Babushkina, S. V. (1992b). Atmospheric transparency variations associated with geomagnetic disturbances. *Journal of Atmospheric and Terrestrial Physics* 54, 1135-1138.

Pudovkin, M. I., and Morozova, A. L. (1997). Time evolution of the temperature altitudinal profile in the lower atmosphere during solar proton events. *Journal of Atmospheric and Solar-Terrestrial Physics* 59, 2159-2166.

Pudovkin, M. I., and Morozova, A. L. (1998). Time variation of atmospheric pressure and circulation associated with temperature changes during solar proton events. *Journal of Atmospheric and Solar-Terrestrial Physics* 60, 1729-1737.

Pudovkin, M. I., and Raspopov, O. M. (1992). The mechanism of action of solar activity on the state of the lower atmosphere and meteorological parameters. *Geomagnetism and Aeronomy* 32, 593-608.

Pudovkin, M. I., and Veretenenko, S. V. (1996). Variations of the cosmic rays as one of the possible links between the solar activity and the lower atmosphere. *Advances in Space Research* 17, 161-164.

Pudovkin, M. I., Veretenenko, S. V., Pellinen, R., and Kyro, E. (1996). Cosmic ray variation effects in the temperature of the high-latitudinal atmosphere. *Advances in Space Research* 17, 165-168.

Pudovkin, M. I., Veretenenko, S. V., Pellinen, R., and Kyro, E. (1997). Meteorological characteristic changes in the high-latitudinal atmosphere associated with Forbush decreases of the galactic cosmic rays. *Advances in Space Research* 20, 1169-1172.

Pueschel, R. F. (1996). Stratospheric aerosols: formation, properties, effects. *Journal of Aerosol Science* 27, 383-402.

Rahmstorf, S., and Alley, R. (2002). Stochastic resonance in glacial climate. *Eos, Transactions* 83, 129, 135.

Rees, D. (1995). Observations and modelling of ionospheric and thermospheric disturbances during major geomagnetic storms: A review. *Journal of Atmospheric and Terrestrial Physics* 57, 1433-1457.

Reichel, R., Thejll, P., and Lassen, K. (2001). The cause-and-effect relationship of solar cycle length and the northern hemisphere air surface temperature. *Journal of Geophysical Research* 106, 15635-15641.

Reid, G. C. (1999). Solar variability and its implications for the human environment. *Journal of Atmospheric and Solar-Terrestrial Physics* 61, 3-14.

Richardson, I. G., Cliver, E. W., and Cane, H. V. (2000). Sources of geomagnetic activity over the solar cycle: relative importance of coronal mass ejections, high-speed streams, and slow solar wind. *Journal of Geophysical Research* 105, 18203-18213.

Richmond, A. D., and Lu, G. (2000). Upper-atmospheric effects of magnetic storms: a brief tutorial. *Journal of Atmospheric and Solar-Terrestrial Physics* 62, 1115-1127.

Roberts, W. O., and Olson, R. H. (1973). Geomagnetic storms and wintertime 300-mb trough development in the North Pacific-North America Area. *Journal of Atmospheric Science* 30, 135-140.

Robock, A. (2001). Stratospheric forcing needed for dynamical seasonal prediction. *Bulletin of the American Meteorological Society* 82, 2189-2192.

Rodwell, M. J., Rowell, D. P., and Folland, C. K. (1999). Oceanic forcing of the wintertime North Atlantic Oscillation and European climate. *Nature* 398, 320-323.

Rogers, R. R., and You, M. K. (1989). “A short course in cloud physics.” Pergamon Press, Oxford. 293 pages.

Roldugin, V. K., and Vashenyuk, E. V. (1994). Atmospheric transparency variation caused by cosmic rays. *Geomagnetism and Aeronomy (English Translation)* 34, 251-253.

Ruzmaikin, A. (1999). Can El Niño amplify the solar forcing of climate? *Geophysical Research Letters* 26, 2255-2258.

Rycroft, M. J., Israelsson, S., and Price, C. (2000). The global atmospheric electric circuit, solar activity and climate change. *Journal of Atmospheric and Solar Terrestrial Physics* 62, 1563-1576.

Sabine, E. (1852). On periodical laws discoverable in the mean effect of the larger magnetic disturbances. *Philosophical Transactions of the Royal Society (London)*, 103-125.

Sakurai, T. (2002). Eleven-year solar cycle periodicity in sky brightness observed at Norikura, Japan. *Earth Planets Space* 54, 153-157.

Salby, M. L., and Shea, D. J. (1991). Correlations between solar activity and the Atmosphere: An unphysical explanation. *Journal of Geophysical Research* 96, 22579-22595.

Salby, M., and Callaghan, P. (2000). Connection between the solar cycle and the QBO: the missing link. *Journal of Climate* 13, 2652-2662.

Samsom, J. C., and Yeung, K. L. (1986). Some generalization on the method of superposed epoch analysis. *Planetary and Space Sciences* 34, 1133-1142.

Sarewitz, D., and Pielke, R. (1999). Prediction in science and policy. *Technology in Society* 21, 121-133.

Sato, M., Hansen, J. E., McCormick, M. P., and Pollack, J. B. (1993). Stratospheric aerosol optical depths, 1850-1990. *Journal of Geophysical Research* 98, 22987-22994.

Schlegel, K., Diendorfer, G., Thern, S., and Schmidt, M. (2001). Thunderstorms, lightning and solar activity – Middle Europe. *Journal of Atmospheric and Solar-Terrestrial Physics* 63, 1705-1713.

Schreiber, H. (1998). On the periodic variations of geomagnetic activity indices Ap and ap. *Annales Geophysicae* 16, 510-517.

Schuurmans, C. J. E. (1991). Changes of the coupled troposphere and lower stratosphere after solar activity events. *Journal of Geomagnetism and Geoelectricity* 43 (Supplement), 767-773.

Schwabe, H. (1844). Sonnen-beobachtungen im jahre 1843. *Astronomische Nachrichten* 21, 233-236.

Shabbar, A., Huang, J., and Higuchi, K. (2001). The relationship between the wintertime North Atlantic Oscillation and blocking episodes in the North Atlantic. *International Journal of Climatology* 21, 355-369.

Shindell, D. T., Miller, R. L., Schmidt, G. A., and Pandolfo, L. (1999a). Simulation of recent northern winter climate trends by greenhouse-gas forcing. *Nature* 399, 452-455.

Shindell, D. T., Schmidt, G. A., Mann, M. E., Rind, D., and Waple, A. (2001b). Solar forcing of regional climate change during the Maunder Minimum. *Science* 294, 2149-2152.

Shindell, D. T., Schmidt, G. A., Miller, R. L., and Rind, D. (2001a). Northern hemisphere winter climate response to greenhouse gas, ozone, solar, and volcanic forcing. *Journal of Geophysical Research* 106, 7193-7210.

Shindell, D., Rind, D., Balachandran, N., Lean, J., and Lonergan, P. (1999b). Solar cycle variability, ozone, and climate. *Science* 284, 305-309.

Siscoe, G. (2000). The space-weather enterprise: past, present, future. *Journal of Atmospheric and Solar-Terrestrial Physics* 62, 1223-1232.

Slonosky, V. C., and Yiou, P. (2001). The North Atlantic Oscillation and its relationship with near surface temperature. *Geophysical Research Letters* 28, 807-810.

Slonosky, V. C., Jones, P. D., and Davies, T. D. (2000). Variability of the surface atmospheric circulation over Europe 1774-1995. *International Journal of Climatology* 20, 1875-1897.

Smith, R. W. (1998). Vertical winds: a tutorial. *Journal of Atmospheric and Solar-Terrestrial Physics* 60, 1425-1434.

Solanki, S. K., and Fligge, M. (1999). A reconstruction of total solar irradiance since 1700. *Geophysical Research Letters* 26, 2465-2468.

Soukharev, B. E. (1997). The interannual variability of temperature in the polar stratosphere during the winter: the influence of the QBO phase and an 11-year solar cycle. *Journal of Atmospheric and Solar-Terrestrial Physics* 59, 469-477.

Stagg, J. M. (1931). Atmospheric pressure and the state of the earth's magnetism. *Nature* 127, 402.

Stening , R. J. (1994). An investigation of solar activity effects in Australian radiosonde data. *Journal of Atmospheric and Terrestrial Physics* 56, 543-553.

Stephens, M. A. (1974). EDF Statistics for goodness of fit and some comparisons. *Journal of the American Statistical Society* 69, 730-737.

Stephenson, D. B., Pavan, V., and Bojariu, R. (2000). Is the North Atlantic Oscillation a random walk? *International Journal of Climatology* 20, 1-18.

Stern, D. I., and Kaufmann, R. K. (1999). Econometric analysis of global climate change. *Environmental Modelling and Software* 14, 597-605.

Storini, M. (2001). Geomagnetic storm effects on the earth's ozone layer. *Advances in Space Research* 27, 1965-1974.

Svensmark, H. (1998). Influence of cosmic rays on earth's climate. *Physical Review Letters* 81, 5027-5030.

Svensmark, H., and Friis-Christensen, E. (1997). Variation of cosmic ray flux and global cloud coverage – a missing link in solar-climate relationships. *Journal of Atmospheric and Solar-Terrestrial Physics* 59, 1225-1232.

Svensmark, H., and Friis-Christensen, E. (2000). Reply to comments on "Variation of cosmic ray flux and global cloud coverage – a missing link in solar-climate relationships". *Journal of Atmospheric and Solar-Terrestrial Physics* 62, 79-80.

Swinbank, R., and Ortland, D. A. (2000). Compilation of wind data for the UARS reference atmosphere project. *COSPAR* http://www.sparc.sunysb.edu/html/urap/html.

Sytinskiy, A. D., and Postnikov, A. N. (1995). Solar activity, atmospheric circulation, and flow rate of the Volga River. *Geomagnetism and Aeronomy (English Translation)* 35, 245-249.

Taylor Jr., H. A. (1986). Selective factors in sun-weather research. *Reviews of Geophysics* 24, 329-348.

Taylor, A. H., Allen, J. I., and Clark, P. A. (2002). Extraction of a weak climatic signal by an ecosystem. *Nature* 416, 629-632.

Thejll, P., and Lassen, K. (2000). Solar forcing of the northern hemisphere land air temperature: New data. *Journal of Atmospheric and Solar-Terrestrial Physics* 62, 1207-1213.

Thejll, P., Christiansen, B., and Gleisner, H. (Submitted, 2002). On correlations between the North Atlantic Oscillation, geopotential heights, and solar-activity proxies. *Geophysical Research Letters*.

Thompson, D. W. J., and Solomon, S. (2002). Interpretation of recent southern hemisphere climate change. *Science* 296, 895-899.

Thompson, D. W. J., Wallace, J. M., and Hegerl, G.C. (2000). Annular modes in the extratropical circulation. Part II: Trends. *Journal of Climate* 13, 1018-1036.

Thompson, D. W. J., Baldwin, M. P., and Wallace, J. M. (2002). Stratospheric connection to northern hemisphere wintertime weather: implications for prediction. *Journal of Climate* 15, 1421-1428.

Thompson, D. W., and Wallace, J. M. (1998). The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. *Geophysical Research Letters* 25, 1297-1300.

Thompson, D. W., and Wallace, J. M. (2000). Annular modes in the extratropical circulation. Part I: Month-to-month variability. *Journal of Climate* 13, 1000-1016.

Tinsley, B. A. (1996a). Correlations of atmospheric dynamics with solar wind-induced changes of air-earth current density into cloud tops. *Journal of Geophysical Research* 101, 29701-29714.

Tinsley, B. A. (1996b). Solar wind modulation of the global electric circuit and apparent effects on cloud microphysics, latent heat release, and tropospheric dynamics. *Journal of Geomagnetism and Geoelectricity* 48, 165-175.

Tinsley, B. A., and Deen, G. W. (1991). Apparent tropospheric response to MeV-GeV particle flux variations: A connection via electrofreezing of supercooled water in high-level clouds? *Journal of Geophysical Research* 96, 22283-22296.

Tinsley, B. A., and Heelis, R. A. (1993). Correlations of atmospheric dynamics with solar activity. Evidence for a connection via the solar wind, atmospheric electricity, and cloud microphysics. *Journal of Geophysical Research* 98, 10375-10384.

Tinsley, B. A., Brown, G. M., and Scherrer, P. H. (1989). Solar variability influences on weather and climate: possible connections through cosmic ray fluxes and storm intensification. *Journal of Geophysical Research* 94, 14783-14792.

Toon, O. B., and Pollack, J. B. (1982). Stratospheric aerosols and climate. *In* “The Stratospheric Aerosol Layer.” (R. C. Whitten, Ed.), pp. 121-146. Springer-Verlag, Berlin.

Torrence, C., and Compo, G. P. (1998). A practical guide to wavelet analysis. *Bulletin of the American Meteorological Society,* 79, 61-78.

Tourre, Y. M., Rajagopalan, B., and Kushnir, Y. (1999). Dominant patterns of climate variability in the Atlantic Ocean during the last 136 years. *Journal of Climate* 12, 2285-2299.

Troshichev, O. A., and Gabis, I. P. (1998). Variations of solar UV irradiance related to short-term and medium-term changes of solar activity. *Journal of Geophysical Research* 103, 20659-20667.

Tsimplis, M. N., and Josey, S. A. (2001). Forcing of the Mediterranean Sea by atmospheric oscillations over the North Atlantic. *Geophysical Research Letters* 28, 803-806.

Tsitas, S.R., and Yung, Y.L. (1996). The effect of volcanic aerosols on ultraviolet radiation in Antarctica. *Geophysical Research Letters* 23, 157-160.

Tsurutani, B. T., and Gonzalez, W. D. (1998). Magnetic Storms. *In* "From the sun: Auroras, magnetic storms, solar flares, cosmic rays." (S. T. Suess, and B. T. Tsurutani, Eds.), pp. 57-66. AGU, Washington.

van Geel, B., Raspopov, O. M., Renssen, H., van der Plicht, J., Dergachev, V. A., and Meijer, H. A. J. (1999). The role of solar forcing upon climate change. *Quaternary Science Reviews* 18, 331-338.

van Loon, H., and Labitzke, K. (1994). The 10-12-year atmospheric oscillation. *Meteorologische Zeitschrift* 3, 259-266.

van Loon, H., and Labitzke, K. (1999). The signal of the 11-year solar cycle in the global stratosphere. *Journal of Atmospheric and Solar-Terrestrial Physics* 61, 53-61.

Varotsos, C. (1989). Comment on connections between the 11-year solar cycle, the Q.B.O. and total ozone. *Journal of Atmosphere and Terrestrial Physics* 51, 367-370.

Venegas, S. A., and Mysak, L. A. (2000). Is there a dominant timescale of natural climate variability in the Arctic? *Journal of Climate* 13, 3412-3434.

Veretenenko, S. V., and Pudovkin, M. I. (1995). The galactic cosmic ray Forbush decrease effects on total cloudiness variations. *Geomagnetism and Aeronomy (English Translation)* 34, 463-468.

Veretenenko, S. V., and Pudovkin, M. I. (1997). Effects of the galactic cosmic ray variations on the solar radiation input in the lower atmosphere. *Journal of Atmospheric and Solar-Terrestrial Physics* 59, 1739-1746.

Veretenenko, S. V., and Pudovkin, M. I. (2000). Latitudinal dependence of helio/geophysical effects on the solar radiation input to the lower atmosphere. *Journal of Atmospheric and Solar-Terrestrial Physics* 62, 567-571.

Viereck, R. A., and Puga, L. C. (1999). The NOAA Mg II core-to-wing solar index: construction of a 20-year time series of chromospheric variability from multiple satellites. *Journal of Geophysical Research* 104, 9995-10005.

Viereck, R. L., Puga, L., McMullin, D., Judge, D., Weber, M., and Tobiska, W. K. (2001). The Mg II index: a proxy for solar EUV. *Geophysical Research Letters* 28, 1343-1346.

Vovk, V. Y., Egorova, L. V., and Moskvin, I. V. (2000). Effects of GCR Forbush decreases on atmospheric parameters in the Antarctic. *Geomagnetism and Aeronomy* 40, 792-798.

Vovk, V. Y., Yegoroa, L. V., and Moskin, I. V. (1994). Evaluation of correlation between varitions of absorption of cosmic noise and near-Earth atmospheric pressure in Antarctica. *Geomagnetism and Aeronomy (English Translation)* 34, 118-120.

Wallace, J. M., and Thompson, D. W. J. (2002). Annular modes and climate prediction. *Physics Today* 55, 28-33.

Wallace. (2000). North Atlantic Oscillation/Northern hemisphere annular mode: one phenomenon, two paradigms. *Quarterly Journal of the Royal Meteorological Society* 126, 791-805.

Watari, S., and Watanabe, T. (1998). The solar drivers of geomagnetic disturbances during solar minimum. *Geophysical Research Letters* 25, 2489-2492.

Webb, D. F. (2000). Understanding CMEs and their source regions. *Journal of Atmospheric and Solar-Terrestrial Physics* 62, 1415-1426.

Webb, D. F., and Howard, R. A. (1994). The solar cycle variation of coronal mass ejections and the solar wind mass flux. *Journal of Geophysical Research* 99, 4201-4220.

Webb, D. F., Johnston, J. C., and Radick, R. R. (2002). The solar mass ejection imager (SMEI): a new tool for space weather. *EOS Transactions* 83, 33,38-39.

Wheeler, D. (2001). A verification of UK gale forecasts by the 'solar weather technique': October 1995-September 1997. *Journal of Atmospheric and Solar-Terrestrial Physics* 63, 29-34.

Wilcox, J. M., Scherrer, P. H., and Hoeksema, J. T. (1983). Interplanetary magnetic field and tropospheric circulation. *In* "Weather and Climate Responses to Solar Variations." (B. M. McCormac, Ed.), pp. 365-379. Colorado Associated University Press, Boulder.

Wilcox, J. M., Scherrer, P. H., Svalgaard, L., Roberts, W. O., and Olsen, R. H. (1973). Solar magnetic sector structure: relation to circulation of the earth's atmosphere. *Science* 180, 185-186.

Woodbridge, D. D. (1971). Comparison of geomagnetic storms and trough development at solar activity maximum and minimum. *Planetary and Space Science* 19, 821-826.

Woodworth, P. L. (1985). A world-wide search for the 11-yr solar cycle in mean sea-level records. *Geophysical Journal of the Royal Astronomical Society* 80, 743-755.

Wunsch, C. (1999). The interpretation of short climate records, with comments on the North Atlantic and Southern Oscillations. *Bulletin of the American Meteorological Society* 80, 245-255.

Yu, F. (2002). Altitude variations of cosmic ray induced production of aerosols: Implications for global cloudiness and climate. *Journal of Geophysical Research* 107, 10.1029/2001JA000248.

Zhou, K., and Butler, C. J. (1998). A statistical study of the relationship between the solar cycle length and tree-ring index values. *Journal of Atmospheric and Solar-Terrestrial Physics* 60, 1711-1718.

Zirin, H. (1988). "Astrophysics of the sun." Cambridge University Press, Cambridge. 433 pages.

Appendix A

A1. Intradiurnal surface pressure variations at Aberdeen

Stagg's (1931) striking results showing that surface pressure at Aberdeen varied with geomagnetic activity are unique because: (a) the variations are intradiurnal and are not evident when daily data are used, (b) the timing of the relationship is unique – there is no delay in the response in atmosphere pressure to geomagnetic activity, and (c) the magnitude of the response is modulated by sunspot activity – the greatest response is evident during solar minimum.

It is surprising that no relationships similar to Stagg's have been discussed in the 70 or so years of literature since then. The aim of the analyses presented here is to explore Stagg's findings and to extend the temporal scope of his study using modern data. For that purpose, atmospheric pressure data for Aberdeen were obtained from the *UK Meteorological Office* (courtesy of Graham Bartlett). The data span 1921 to 1995, and therefore encompass the years of Stagg's study (1922 to 1928). Unfortunately, hourly data are not available and therefore the Aberdeen data used in this study are six-hourly (6h, 12h, 18h, 24h GMT). Values for 12h GMT were of interest as these correspond most closely to the forenoon maximum in Stagg's results. Another notable difference is that the geomagnetic AA index is used in this study, instead of data from De Bilt. It is also important to note that there are some inconsistencies in the pressure data (missing values/mislabelled times) that might have some bearing on the results. In all other regards, the methods employed here are similar to those of *Stagg (1931)*. The five days of highest and lowest geomagnetic activity for each month were selected and mean diurnal inequalities of atmospheric pressure values for these days at 12h were isolated and averaged for each year. It was found that there is no striking variation in atmospheric pressure at 12h in both the entire dataset (1921-1995) and the subset corresponding to Stagg's study (1922-1928), and also that the state of the sunspot cycle has no influence on the results, shown in Figure A1. The figure also shows the temporal nature of the results by plotting the averages for each year. The statistical significance of the results has been tested using paired *t*-tests ($\alpha = 0.05$), comparing the yearly averages of the mean diurnal inequalities for the five highest and lowest geomagnetic AA index days of each month. The six years in which the differences are statistically significant are marked in Figure A1 using solid columns. Given the number of years ($N = 75$), the six significant years barely exceed the 5% of cases expected to be significant solely due to chance. Overall, the results indicate that there is no appreciable difference in atmospheric pressure at Aberdeen associated with geomagnetic activity.

A2. Geomagnetic activity and long-term temperature changes – seasonal aspects

An examination of seasonal dependencies, through the use of monthly data, indicates that there is no seasonal signal in the geomagnetic activity forcing of either southern or northern hemisphere temperature data. The correlation coefficients between geomagnetic activity and hemispheric temperature, for each month, are shown in Table A1. All indices have been smoothed using an 11-point moving average filter, and consequently the effective number of observations for these correlations does not exceed two for any month. Accordingly, none of the correlations are statistically significant at the 95% confidence level. The correlations are generally of a similar magnitude as the annual global temperature-AA index correlations, though the northern hemisphere correlations are slightly lower. If there is, in fact, a relationship between solar-modulated geomagnetic activity and temperature then the influence of anthropogenic climate change, which is more pronounced in the northern hemisphere, can explain the reduction in the correlation coefficients.

The temporal nature of the correlations was also examined using 11-point sliding correlations. The results (not shown) reveal that all monthly correlations are temporally inconsistent, indicating once again that it is only the long-term trend that is shared between solar and temperature variations.

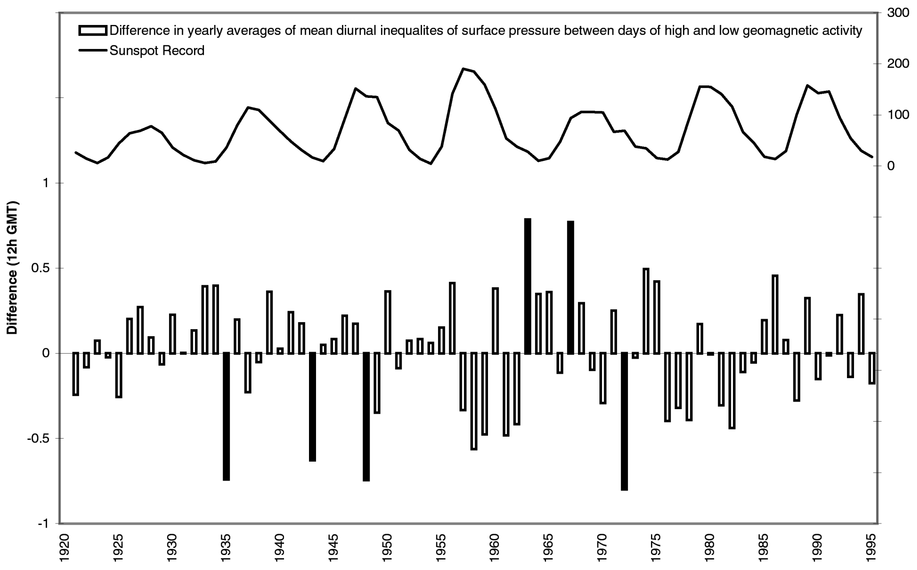

Figure A1. Differences in mean diurnal inequalities in Aberdeen surface pressure at 12h GMT for days of high and low geomagnetic activity. See text for details.

Table A1. Correlation coefficients between long-term changes in monthly northern and southern hemisphere temperature records and the AA index. All indices have been smoothed using an 11-point moving average. The effective number of observations does not exceed two for any month. Consequently, none of the correlations are statistically significant at the 95% confidence level. Furthermore, there is no clear seasonal signal in the monthly results. The northern hemisphere correlations are generally lower than the corresponding southern hemisphere correlations.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
$r(T_{SH},AA)$ 11-pt moving averages	0.85	0.89	0.78	0.86	0.83	0.92	0.75	0.84	0.70	0.86	0.86	0.88
$r(T_{NH},AA)$ 11-pt moving averages	0.77	0.80	0.77	0.87	0.82	0.84	0.71	0.73	0.79	0.86	0.73	0.87

Appendix B

Table B1. Correlation coefficients between the monthly and three-monthly versions of the AA and Antarctic Oscillation indices, 1958-1999. Note that the correlation period for the decadal and interannual variations is 1960-1997 (two years have been lost from each end due to the use of a five-point moving average in the calculation of the decadal variations). The effective number of observations (N_{eff}) due to serial correlation is shown. Correlation coefficients that are significant at the 95% confidence level (using N_{eff}) are highlighted in grey. Note the seasonal nature of the correlations, which are highest for March and the FMA and MAM three-monthly averages.

AA Antarctic Oscillation	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	JFM Ave	FMA Ave	MAM Ave	AMJ Ave	MJJ Ave	JJA Ave	JAS Ave	ASO Ave	SON Ave	OND Ave	NDJ Ave	DJF Ave
Original	-0.06	0.10	0.39	0.04	0.03	0.06	-0.16	-0.08	0.19	0.07	0.19	-0.02	0.35	0.43	0.31	0.11	-0.06	-0.01	-0.01	-0.01	0.12	0.08	0.06	0.12
N_{eff} (N = 42)	35	37	38	35	39	41	36	39	42	41	40	38	28	29	30	33	34	33	34	38	39	40	37	32
Decadal	0.12	0.57	0.66	0.38	0.49	0.23	0.02	0.20	0.15	0.39	0.65	0.24	0.62	0.71	0.59	0.44	0.28	0.22	0.14	0.32	0.59	0.55	0.47	0.42
N_{eff} (N = 38)	4	6	5	5	6	6	6	5	9	8	6	6	4	4	4	5	6	5	5	5	6	6	5	5
Interannual	-0.15	-0.06	0.32	0.06	0.04	-0.21	-0.17	-0.16	0.24	-0.20	-0.08	-0.09	0.31	0.52	0.40	0.07	-0.20	-0.12	0.01	-0.19	-0.16	-0.20	-0.18	0.05
N_{eff} (N = 38)	37	36	34	37	34	33	35	34	33	28	28	35	37	38	37	38	36	36	36	33	30	28	30	36

Table B2. Correlation coefficients between the monthly and three-monthly versions of the AA and Arctic Oscillation indices, 1965-1999. Correlations for the decadal and interannual variations are from 1965-1997 (two years have been lost from the end of the series through the use of the five-point moving average). See Table B1 for details. Also, note the seasonal nature of the correlations, which are highest for January and the three-monthly averages from NDJ to FMA.

AA Arctic Oscillation	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	JFM Ave	FMA Ave	MAM Ave	AMJ Ave	MJJ Ave	JJA Ave	JAS Ave	ASO Ave	SON Ave	OND Ave	NDJ Ave	DJF Ave
Original	0.62	0.21	0.26	-0.01	0.09	-0.05	0.15	0.11	0.02	-0.22	0.09	0.27	0.66	0.40	0.24	0.13	0.11	0.09	0.12	-0.03	0.03	0.24	0.55	0.46
N_{eff} (N = 35)	28	32	32	31	35	32	33	32	34	33	34	34	25	29	31	34	27	31	35	33	32	35	29	27
Decadal	0.82	0.46	0.64	0.02	-0.22	-0.33	0.19	0.44	0.16	-0.05	0.23	0.59	0.79	0.60	0.31	-0.10	-0.06	0.34	0.62	0.57	0.28	0.62	0.76	0.70
N_{eff} (N = 33)	5	6	6	9	8	12	15	5	10	6	6	7	4	5	6	6	11	9	8	7	9	6	5	5
Interannual	0.49	0.11	0.17	0.04	0.27	0.08	0.07	-0.10	0.02	-0.29	0.14	0.18	0.58	0.33	0.20	0.27	0.17	0.00	-0.03	-0.23	0.03	0.12	0.47	0.35
N_{eff} (N = 33)	33	30	32	32	30	28	28	30	25	27	27	30	32	33	33	32	30	28	29	27	28	28	29	31

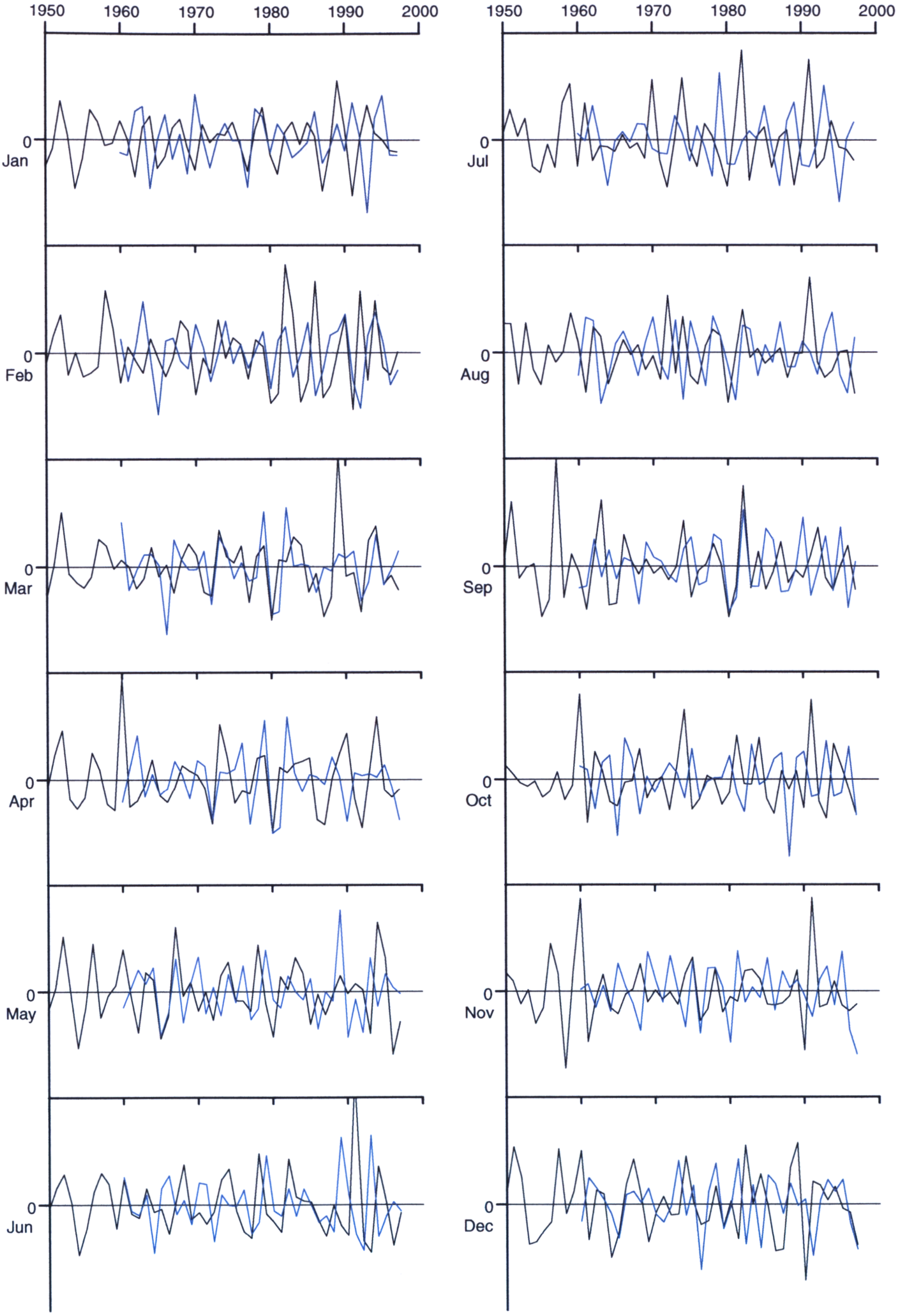

Figure B1. Interannual variations in the monthly AA (black line) and Antarctic Oscillation (blue line) indices. The interannual variations were isolated by subtracting a five-point moving average of each series from the raw data. Note the similarity between geomagnetic activity and the Antarctic Oscillation index for the month of March. There is very little correspondence between the interannual variations of the AA index and the Antarctic Oscillation index for other months. These graphs are discussed in chapter three.

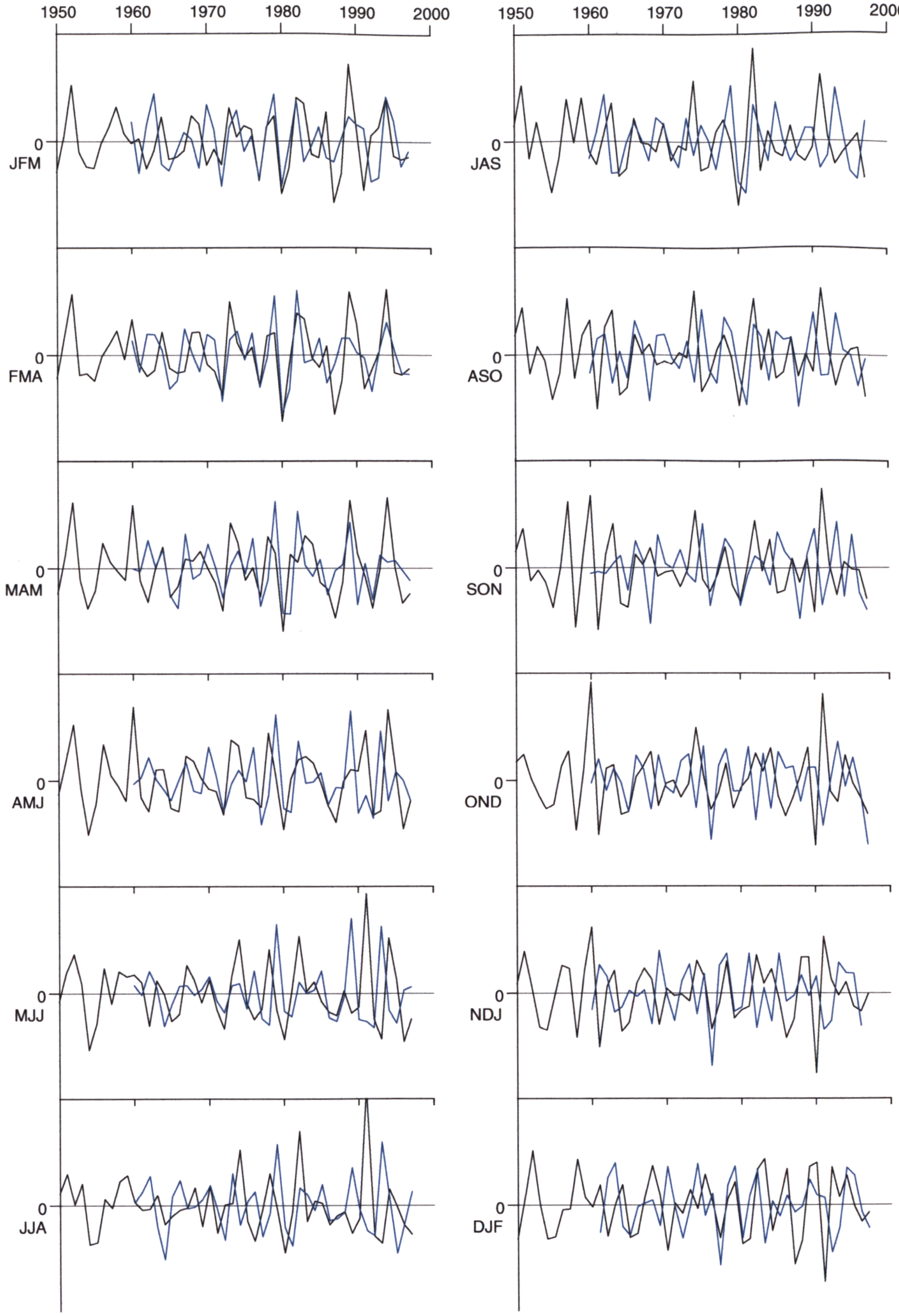

Figure B2. Interannual variations in the three-monthly averages of the AA (black line) and Antarctic Oscillation (blue line) indices. The strongest resemblance between interannual variations of geomagnetic activity and atmospheric circulation in the southern hemisphere is evident in the FMA three-monthly averages. These results are discussed in chapter three.

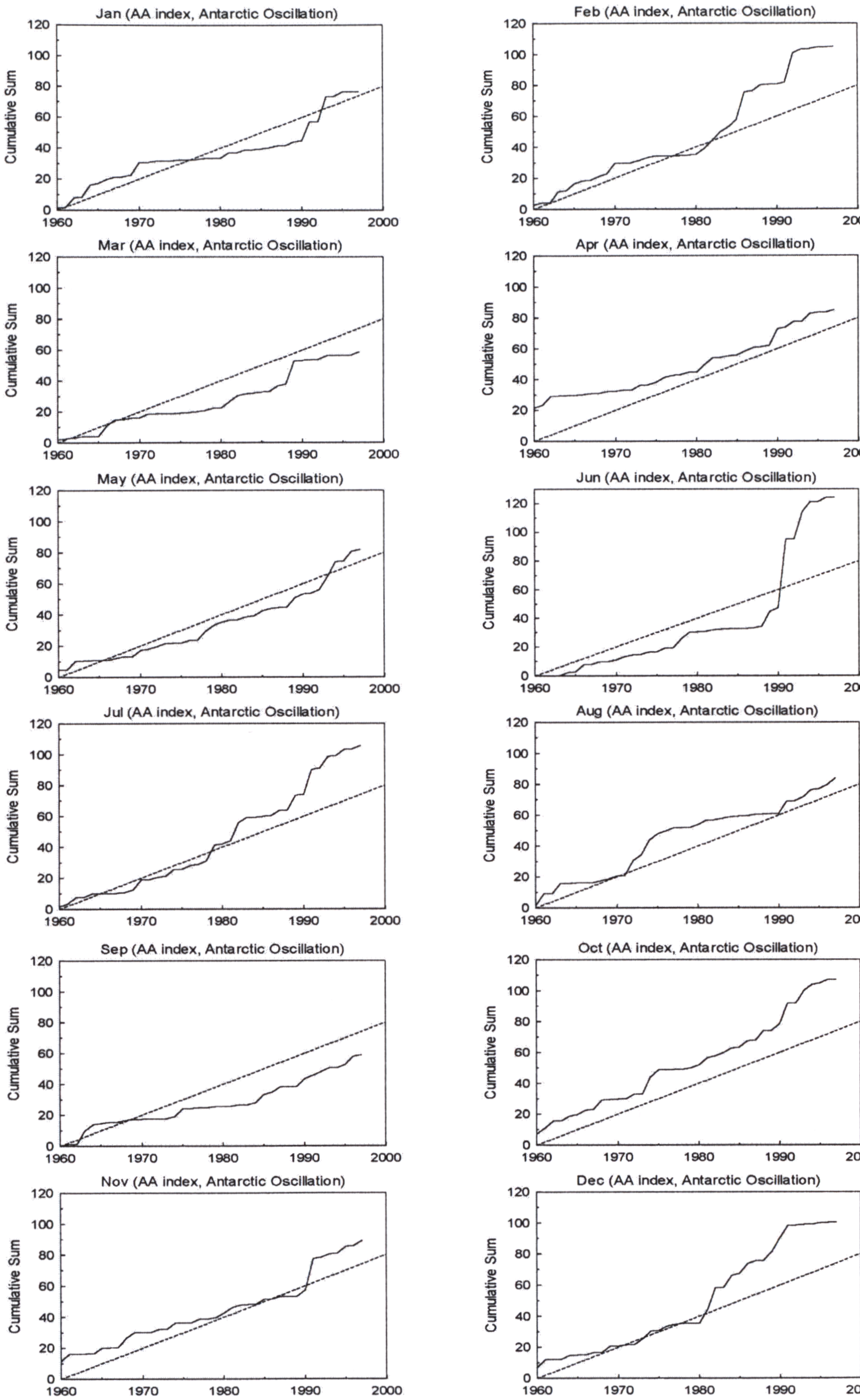

Figure B3. Cumulative sums between interannual variations in the monthly AA and Antarctic Oscillation indices. The cumulative sums process is described in chapter three. The stippled line indicates no correlation. Periods for which the cumulative sums have a zero gradient reflect intervals of high correlation between the two indices.

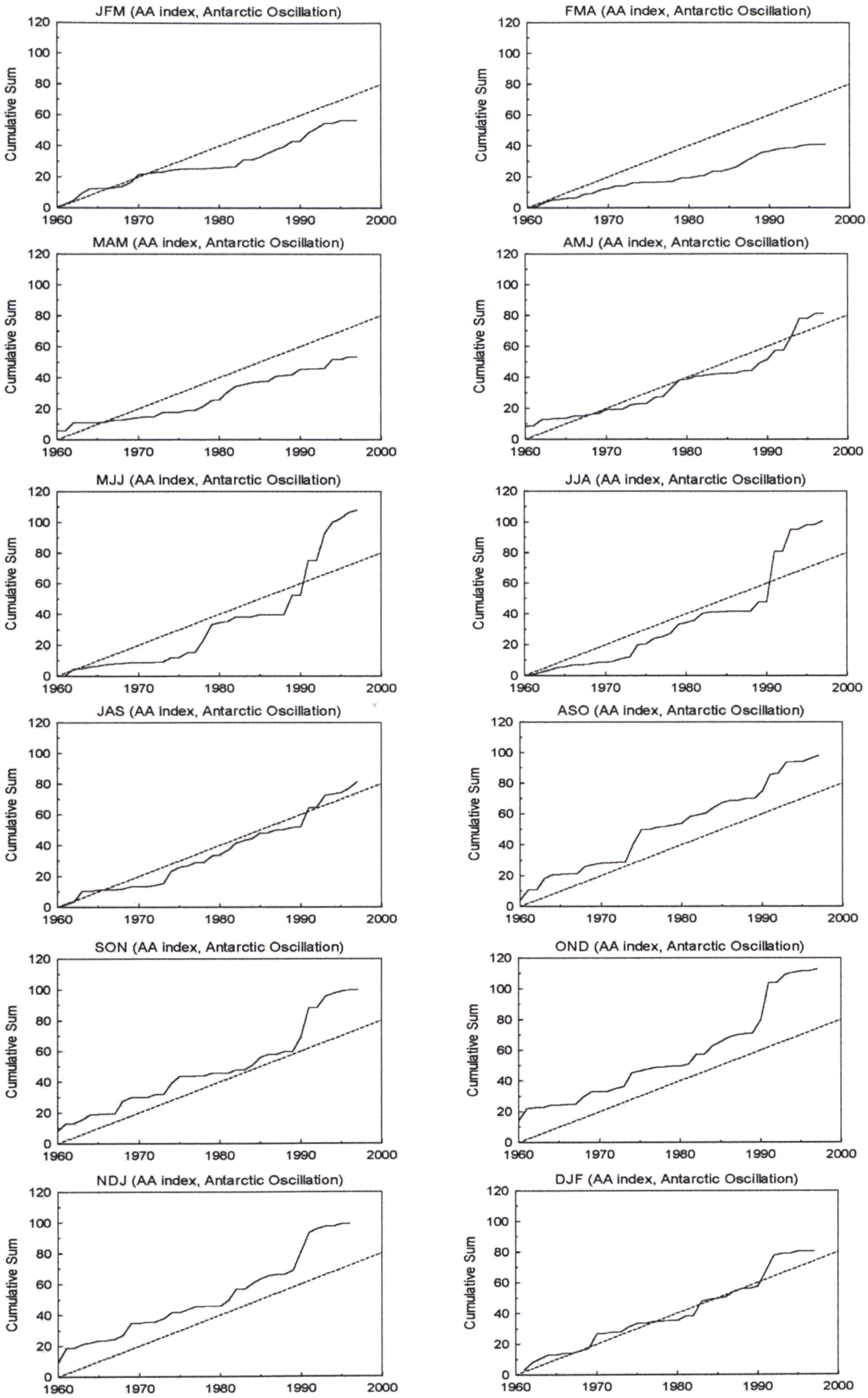

Figure B4. Cumulative sums between interannual variations in the three-monthly averages of the AA and Antarctic Oscillation indices. The slope of the cumulative sums matches that of the stippled line for most of the three-monthly average indices, which indicates no correlation. The main exception is the results for FMA, which indicates a moderate correlation between three-monthly averages of the AA and Antarctic Oscillation indices.

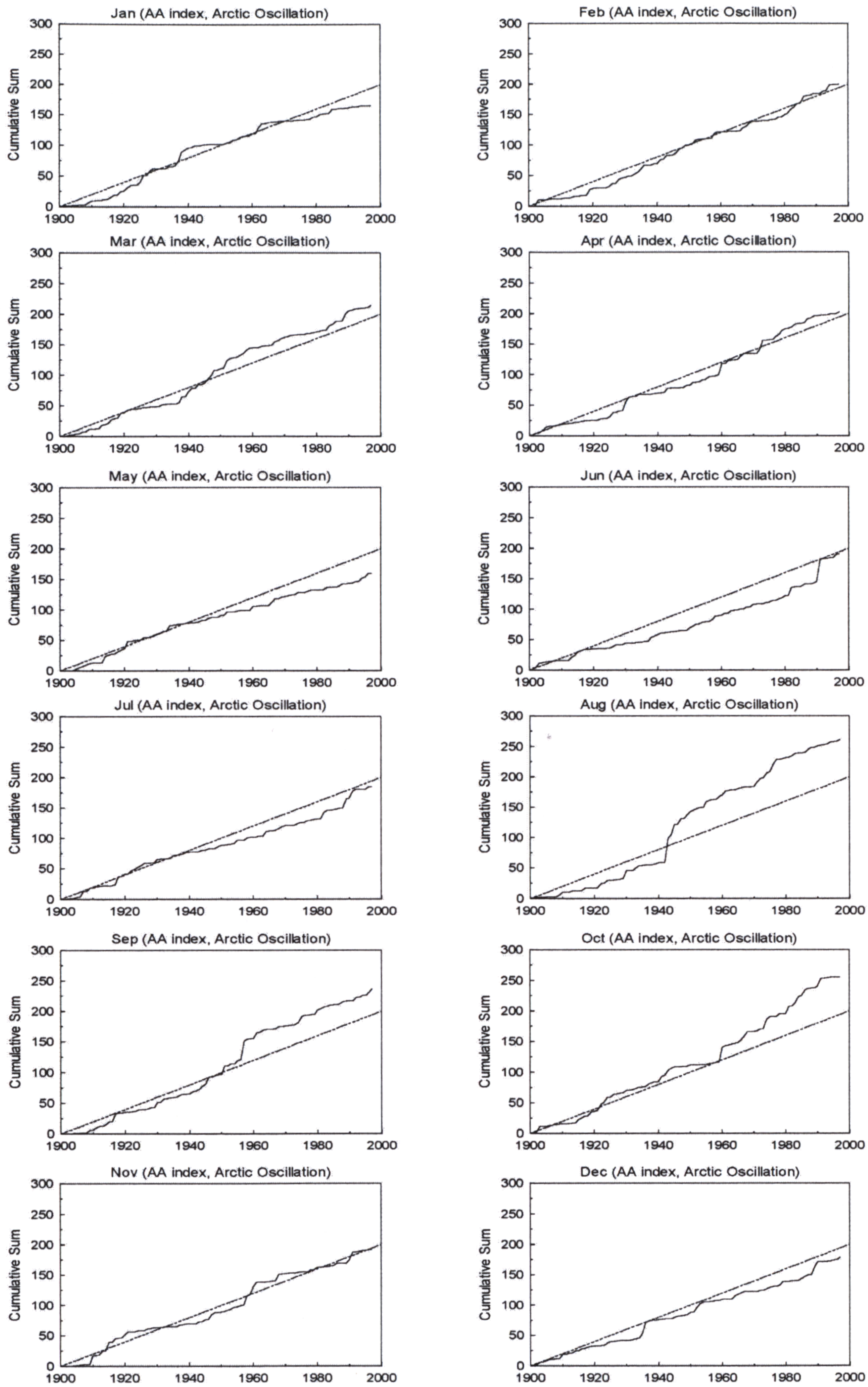

Figure B5. Cumulative sums between interannual variations in the monthly AA and Arctic Oscillation indices. With the exception of the January results the slope of the cumulative sums generally does not differ from the slope of uncorrelated data, indicated by a stippled line. This reveals that, at interannual timescales, there is strong seasonal component to the relationship between the AA index and the Arctic Oscillation.

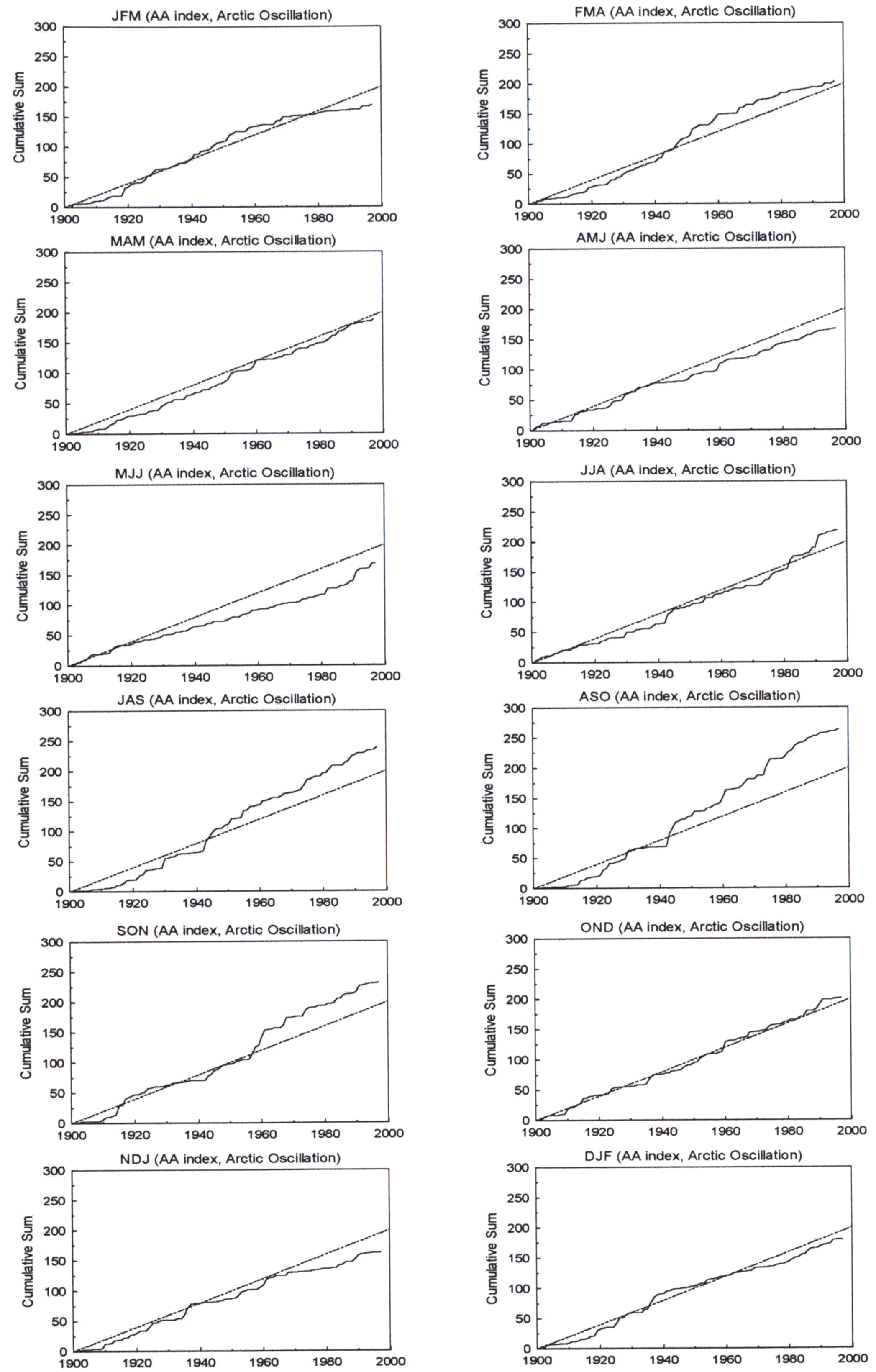

Figure B6. Cumulative sums between interannual variations in the three-monthly averages of the AA and Arctic Oscillation indices. The latter part of the JFM cumulative sums shows a shallow gradient, indicating a positive correlation between geomagnetic activity and the Arctic Oscillation index. Beyond this, most of the cumulative sums do not deviate from the slope of the uncorrelated data, indicated by the stippled lines.

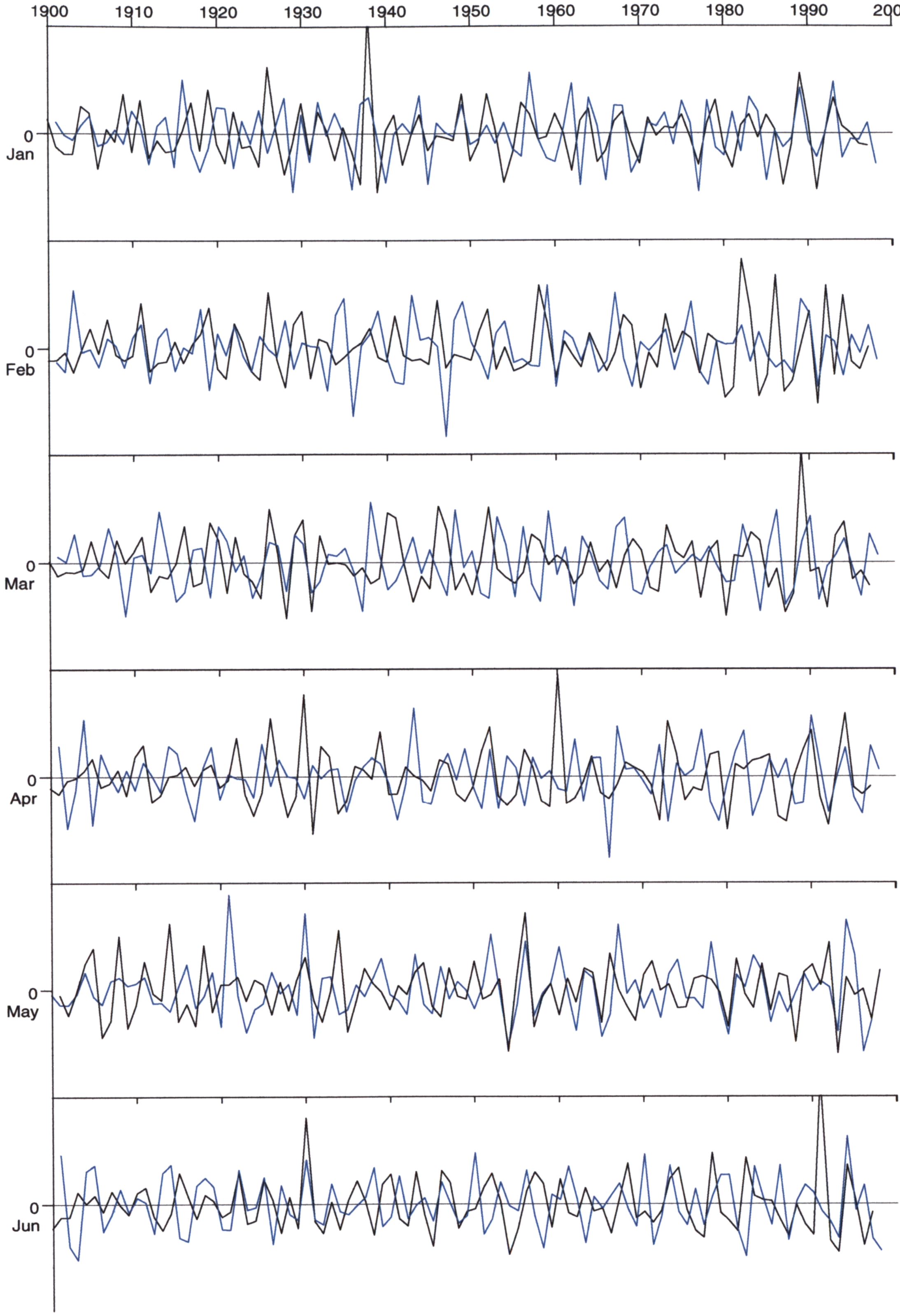

Figure B7. Interannual variations in the monthly AA (black line) and Arctic Oscillation (blue line) indices, January to June. Note the similarity between the indices during January from 1965 onwards.

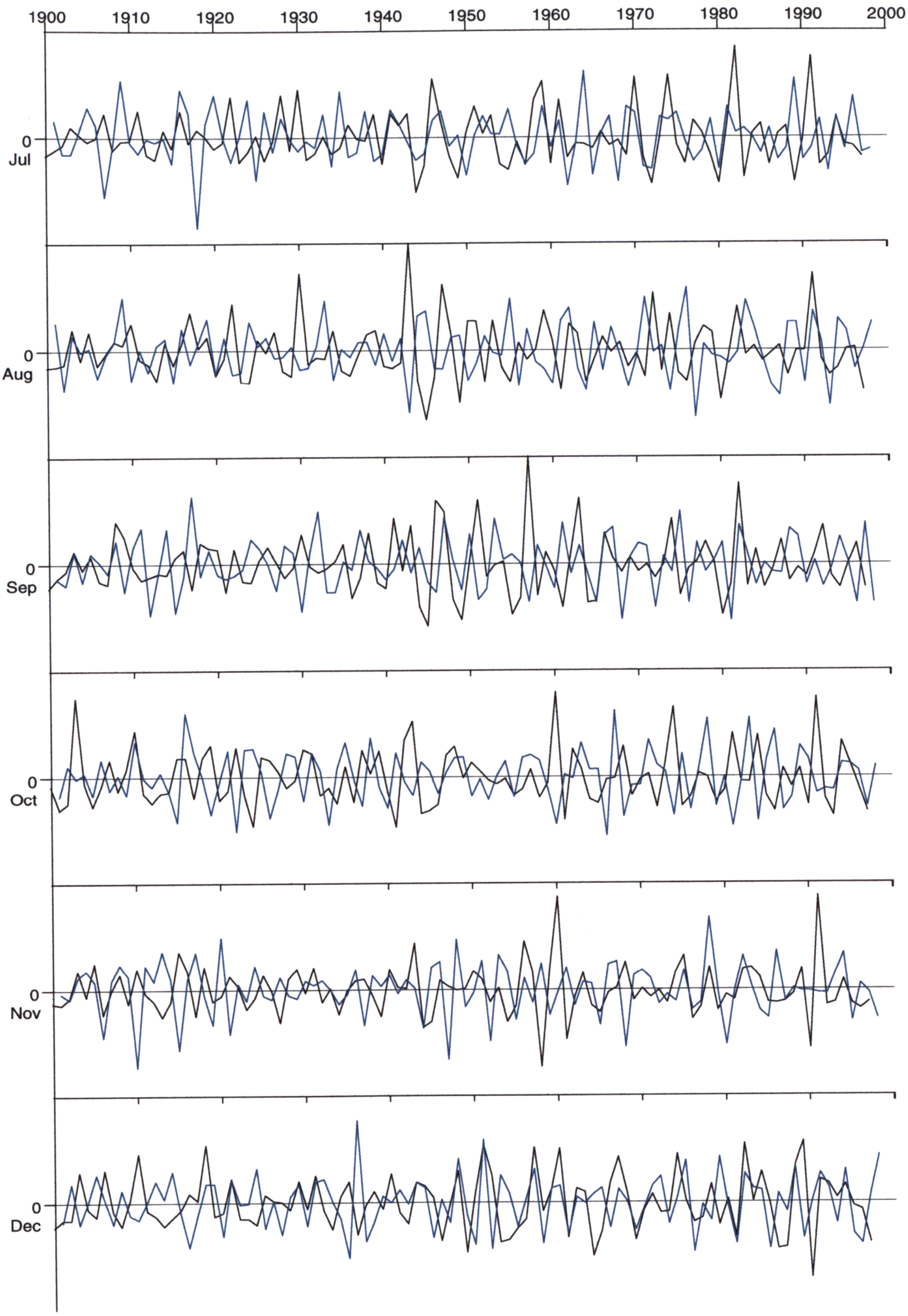

Figure B8. Interannual variations in the monthly AA (black line) and Arctic Oscillation (blue line) indices, July to December. These graphs are discussed in chapter three.

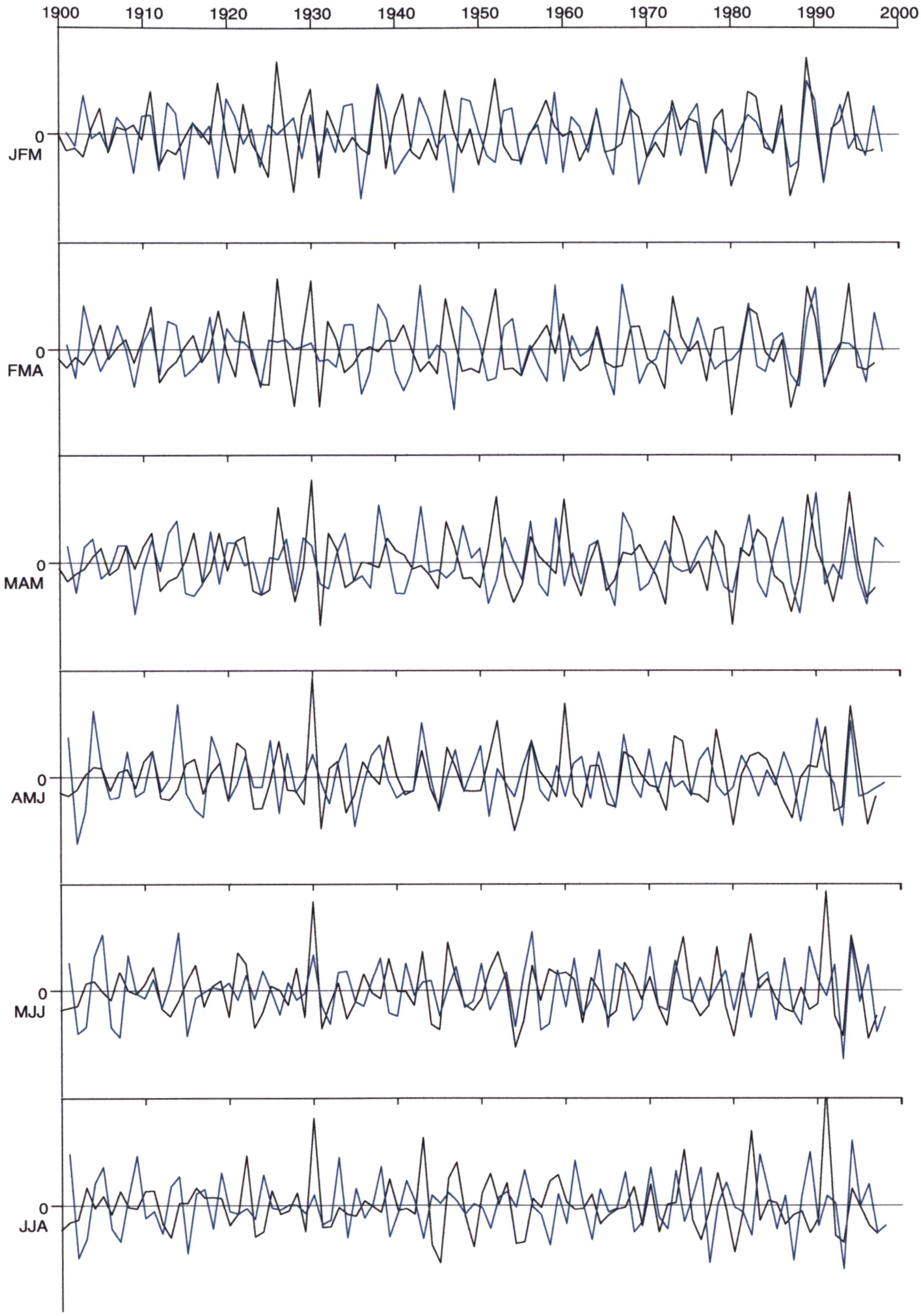

Figure B9. Interannual variations in the three-monthly averages of the AA (black line) and Arctic Oscillation (blue line) indices, JFM to JJA. When examined in conjunction with the cumulative sums shown in Figure B6, this figure indicates that a link between geomagnetic activity and the Arctic Oscillation generally only occurs in the JFM data, after ~1965.

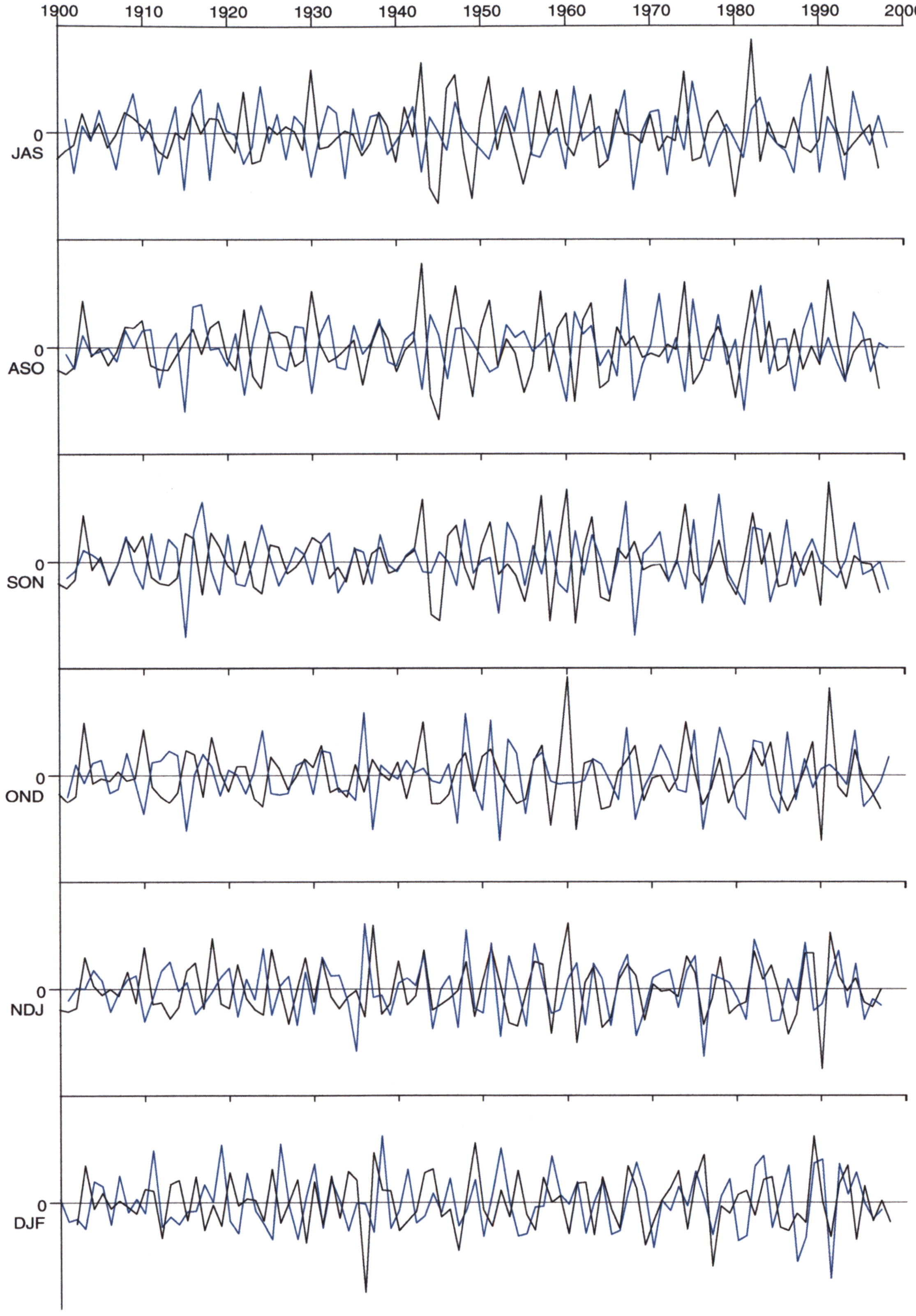

Figure B10. Interannual variations in the three-monthly averages of the AA (black line) and Arctic Oscillation (blue line) indices, JAS to DJF. These resuls are discussed in chapter three.

Table B1. Correlation coefficients between the monthly and three-monthly versions of the AA and Antarctic Oscillation indices, 1958-1999. Note that the correlation period for the decadal and interannual variations is 1960-1997 (two years have been lost from each end due to the use of a five-point moving average in the calculation of the decadal variations). The effective number of observations (N_{eff}) due to serial correlation is shown. Correlation coefficients that are significant at the 95% confidence level (using N_{eff}) are highlighted in grey. Note the seasonal nature of the correlations, which are highest for March and the FMA and MAM three-monthly averages.

AA Antarctic Oscillation	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	JFM Ave	FMA Ave	MAM Ave	AMJ Ave	MJJ Ave	JJA Ave	JAS Ave	ASO Ave	SON Ave	OND Ave	NDJ Ave	DJF Ave
Original	-0.06	0.10	0.39	0.04	0.03	0.06	-0.16	-0.08	0.19	0.07	0.19	-0.02	0.35	0.43	0.31	0.11	-0.06	-0.01	-0.01	-0.01	0.12	0.08	0.06	0.12
N_{eff} (N = 42)	35	37	38	35	39	41	36	39	42	41	40	38	28	29	30	33	34	33	34	38	39	40	37	32
Decadal	0.12	0.57	0.66	0.38	0.49	0.23	0.02	0.20	0.15	0.39	0.65	0.24	0.62	0.71	0.59	0.44	0.28	0.22	0.14	0.32	0.59	0.55	0.47	0.42
N_{eff} (N = 38)	4	6	5	5	6	6	6	5	9	8	6	6	4	4	4	5	6	5	5	5	6	6	5	5
Interannual	-0.15	-0.06	0.32	0.06	0.04	-0.21	-0.17	-0.16	0.24	-0.20	-0.08	-0.09	0.31	0.52	0.40	0.07	-0.20	-0.12	0.01	-0.19	-0.16	-0.20	-0.18	0.05
N_{eff} (N = 38)	37	36	34	37	34	33	35	34	33	28	28	35	37	38	37	38	36	36	36	33	30	28	30	36

Table B2. Correlation coefficients between the monthly and three-monthly versions of the AA and Arctic Oscillation indices, 1965-1999. Correlations for the decadal and interannual variations are from 1965-1997 (two years have been lost from the end of the series through the use of the five-point moving average). See Table B1 for details. Also, note the seasonal nature of the correlations, which are highest for January and the three-monthly averages from NDJ to FMA.

AA Arctic Oscillation	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	JFM Ave	FMA Ave	MAM Ave	AMJ Ave	MJJ Ave	JJA Ave	JAS Ave	ASO Ave	SON Ave	OND Ave	NDJ Ave	DJF Ave
Original	0.62	0.21	0.26	-0.01	0.09	-0.05	0.15	0.11	0.02	-0.22	0.09	0.27	0.66	0.40	0.24	0.13	0.11	0.09	0.12	-0.03	0.03	0.24	0.55	0.46
N_{eff} (N = 35)	28	32	32	31	35	32	33	32	34	33	34	34	25	29	31	34	27	31	35	33	32	35	29	27
Decadal	0.82	0.46	0.64	0.02	-0.22	-0.33	0.19	0.44	0.16	-0.05	0.23	0.59	0.79	0.60	0.31	-0.10	-0.06	0.34	0.62	0.57	0.28	0.62	0.76	0.70
N_{eff} (N = 33)	5	6	6	9	8	12	15	5	10	6	6	7	4	5	6	6	11	9	8	7	9	6	5	5
Interannual	0.49	0.11	0.17	0.04	0.27	0.08	0.07	-0.10	0.02	-0.29	0.14	0.18	0.58	0.33	0.20	0.27	0.17	0.00	-0.03	-0.23	0.03	0.12	0.47	0.35
N_{eff} (N = 33)	33	30	32	32	30	28	28	30	25	27	27	30	32	33	33	32	30	28	29	27	28	28	29	31

Table B3. Correlation coefficients between the monthly and three-monthly versions of the AA and North Atlantic Oscillation indices, 1965-1999. Correlations for the decadal and interannual variations are from 1965-1997 (two years have been lost from the end of the series through the use of the five-point moving average). See Table B1 for details. The magnitude and seasonal pattern of the correlations is very similar to those shown in Table B2.

AA NAO	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	DJF Ave	JFM Ave	FMA Ave	MAM Ave	AMJ Ave	MJJ Ave	JJA Ave	JAS Ave	ASO Ave	SON Ave	OND Ave	NDJ Ave
Original	0.57	0.12	0.31	-0.22	0.04	-0.03	0.03	0.28	0.18	-0.01	0.19	0.18	0.42	0.69	0.42	0.19	-0.04	-0.04	0.11	0.23	0.35	0.35	0.15	0.46
Neff (35)	32	32	35	35	34	33	31	32	35	32	34	35	27	27	29	33	31	27	31	34	33	29	31	30
Decadal	0.90	0.44	0.67	-0.23	-0.52	-0.17	-0.10	0.61	0.03	0.13	0.11	0.58	0.76	0.90	0.68	0.22	-0.27	-0.36	0.34	0.47	0.73	0.34	0.63	0.80
Neff (33)	5	6	7	4	9	9	9	7	13	6	10	10	5	4	4	9	7	12	8	10	8	10	11	6
Interannual	0.35	-0.09	0.27	-0.21	0.34	-0.03	0.17	0.03	0.25	-0.11	0.19	-0.02	0.10	0.57	0.29	0.23	-0.01	0.09	-0.04	0.27	0.28	0.40	-0.08	0.25
Neff (33)	33	29	31	32	30	28	27	31	30	26	27	30	32	32	33	32	32	30	28	29	28	27	26	31

Table B4. Correlation coefficients between the three-monthly versions of the AA index and the two nodes of the North Atlantic Oscillation index, 1965-1999. Correlations for the decadal and interannual variations are from 1965-1997 (two years have been lost from the end of the series through the use of the five-point moving average). See Table B1 for details. Correlations are calculated using sea level pressure data for each node.

	Iceland												Ponta Delgada[1]											
AA Iceland and Ponta Delgada	DJF Ave	JFM Ave	FMA Ave	MAM Ave	AMJ Ave	MJJ Ave	JJA Ave	JAS Ave	ASO Ave	SON Ave	OND Ave	NDJ Ave	DJF Ave	JFM Ave	FMA Ave	MAM Ave	AMJ Ave	MJJ Ave	JJA Ave	JAS Ave	ASO Ave	SON Ave	OND Ave	NDJ Ave
Original	-0.41	-0.68	-0.42	-0.27	0.11	0.02	-0.14	-0.29	-0.21	-0.33	-0.14	-0.49	0.40	0.62	0.41	0.14	0.00	-0.08	-0.05	0.04	0.38	0.15	0.05	0.34
Neff (35)	26	26	32	33	30	27	32	34	35	32	31	29	30	30	29	33	29	29	31	32	33	28	32	30
Decadal	-0.67	-0.85	-0.70	-0.33	0.31	0.32	-0.24	-0.52	-0.39	-0.30	-0.58	-0.80	0.82	0.94	0.72	0.08	-0.19	-0.48	0.02	-0.14	0.47	-0.32	-0.07	0.58
Neff (33)	5	4	4	8	7	11	7	8	7	6	8	5	5	3	4	10	5	5	10	9	7	8	8	8
Interannual	-0.17	-0.58	-0.29	-0.29	0.13	-0.08	-0.03	-0.29	-0.25	-0.37	0.04	-0.30	-0.01	0.40	0.24	0.10	-0.11	0.12	-0.15	0.20	0.29	0.29	-0.15	0.04
Neff (33)	32	32	33	32	32	30	28	30	28	28	26	31	28	30	31	30	30	30	29	28	28	27	27	27

[1] The Ponta Delgada record ends in 1997, rather than 1999 like the Iceland record. Therefore, the actual N (shown in parenthesis next to N_{eff}) is two less than that of the Iceland record.

Appendix C

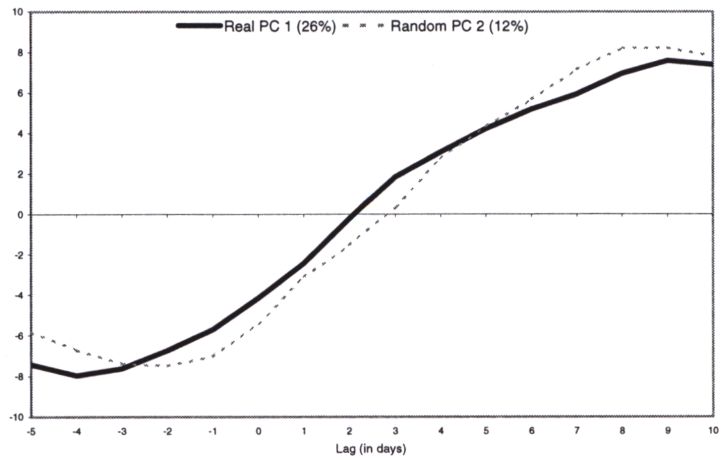

Figure C1. The leading principal component of Antarctic Oscillation index data extracted for intervals centred on days of increased geomagnetic activity. Note the strong similarity between the appearance and weighting of the leading principal component for the real and random key dates. This indicates that geomagnetic activity does not influence the Antarctic Oscillation index at daily timescales, and that the PCA superposed epoch analysis technique is a useful tool for validating results when random key dates are incorporated into the analyses. Note also that the weighting of the leading principal components is high, even though the results are entirely the result of 'noise'. This conflicts with the suggestion, by *Lam and Samsom (1994)*, that the relative weighting of the leading component can be used to gauge the statistical significance of the results. The weighting of the second principal components is 14% for the real data and 12% for the random data. The random component has been inverted to highlight the similarity to the real component

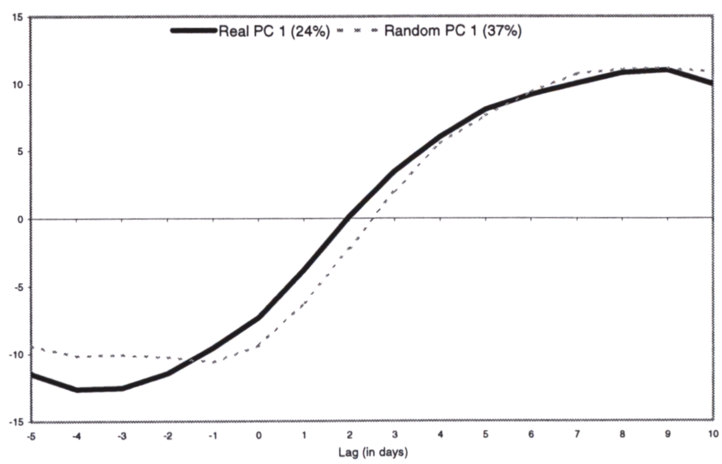

Figure C2. The leading principal component of Arctic Oscillation index data extracted for intervals centred on days of increased geomagnetic activity. Like the results shown in Figure C1, there is a strong similarity in both the appearance and weighting of the real and random principal components. In this case, however, the weighting of the principal component for the random data greatly exceeds that of the real data.

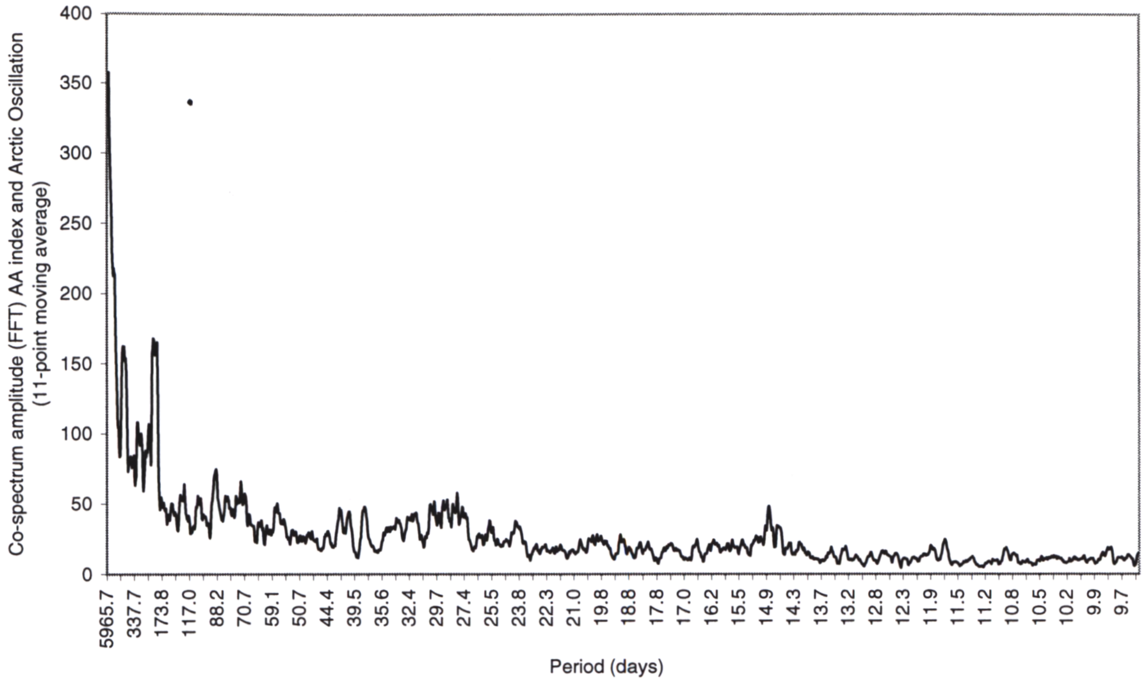

Figure C3. FFT Co-spectrum of the daily AA and Arctic Oscillation indices, 1950-1998. The spectrum has been smoothed using an 11-point moving average. There are minor peaks around periods of 28 and 15 days, which may relate to solar rotation periods. The use of co-spectral analysis is a useful tool for the analysis of noisy meteorological and geophysical data, though the technique has many limitations. These have been described in chapter four.

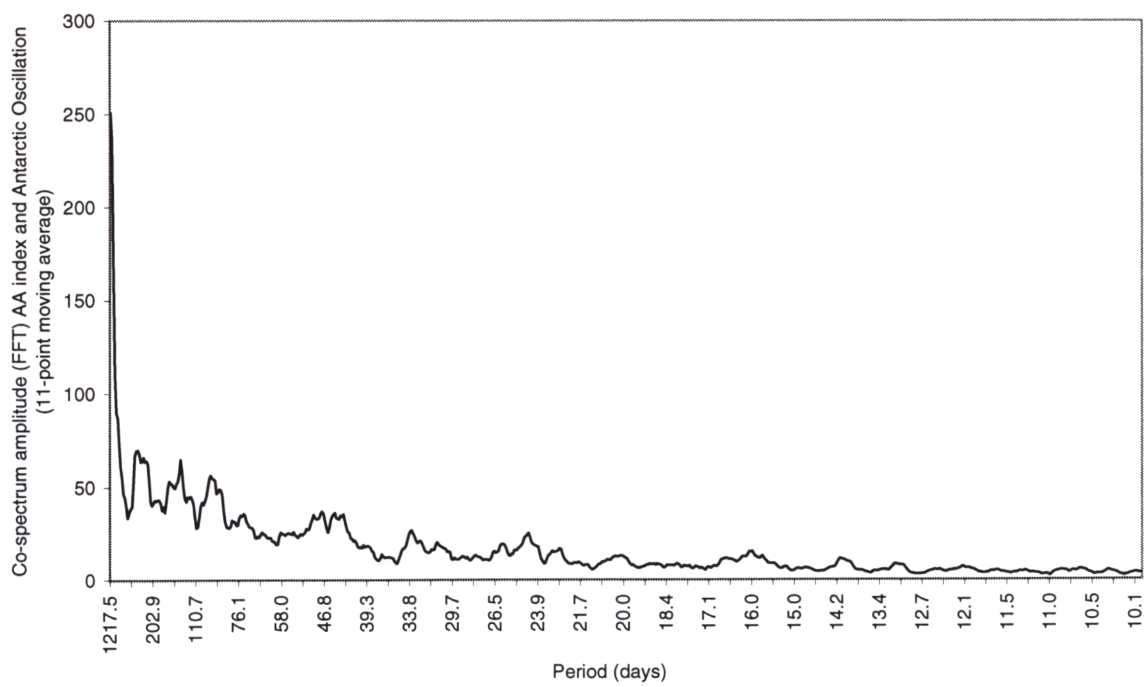

Figure C4. FFT Co-spectrum of the daily AA and Antarctic Oscillation indices, 1979-1998. The spectrum has been smoothed using an 11-point moving average. Although there are no peaks, even minor ones, at known solar periods, the use of co-spectral analysis in solar-weather studies may be warranted. This is largely because the technique is not limited by noise in the same manner as superposed epoch analysis.

Appendix D

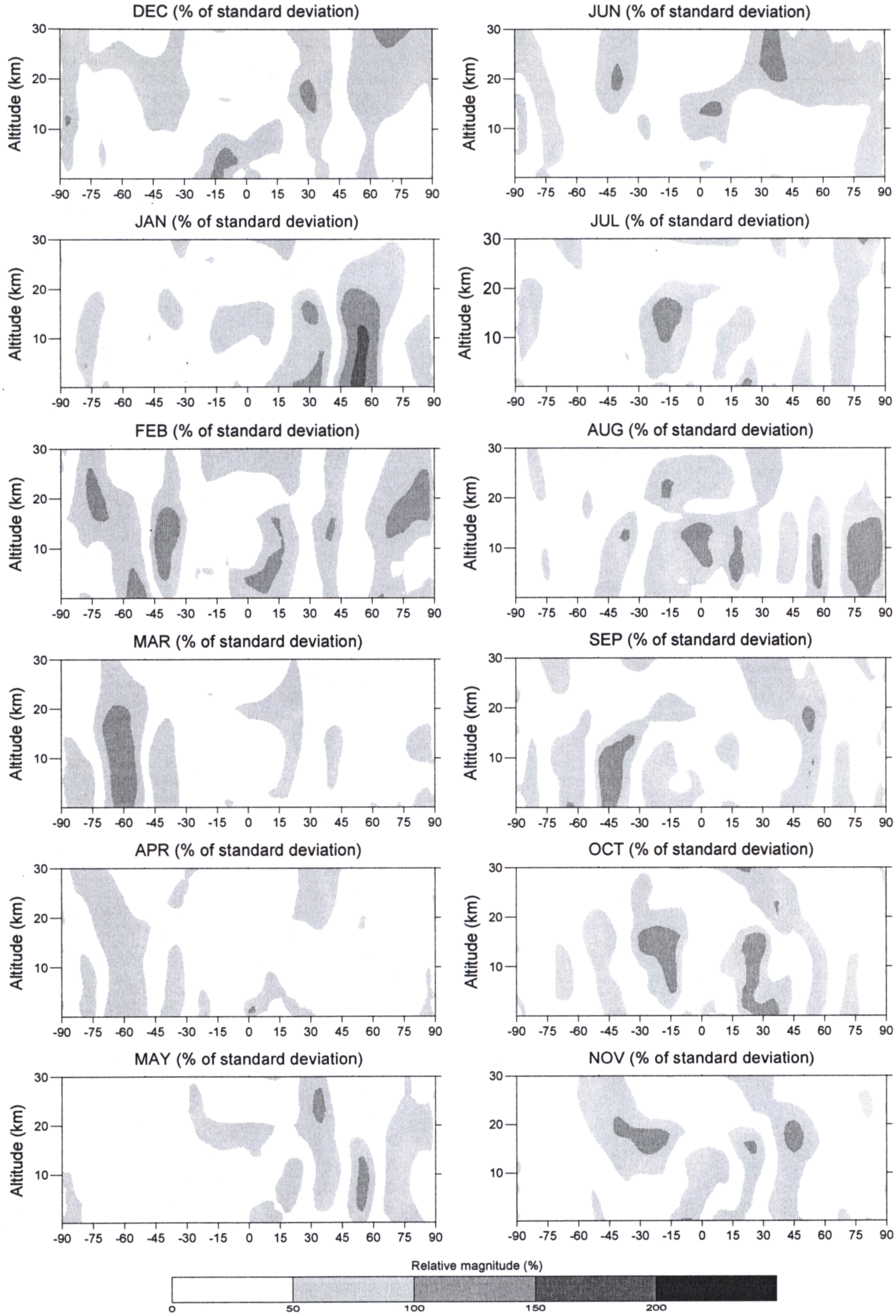

Figure D1. Differences between composites of zonal-mean zonal wind for high and low geomagnetic activity for each month, relative to the standard deviation. The strongest changes, which exceed 150% of the standard deviation, are evident in January in the northern hemisphere.

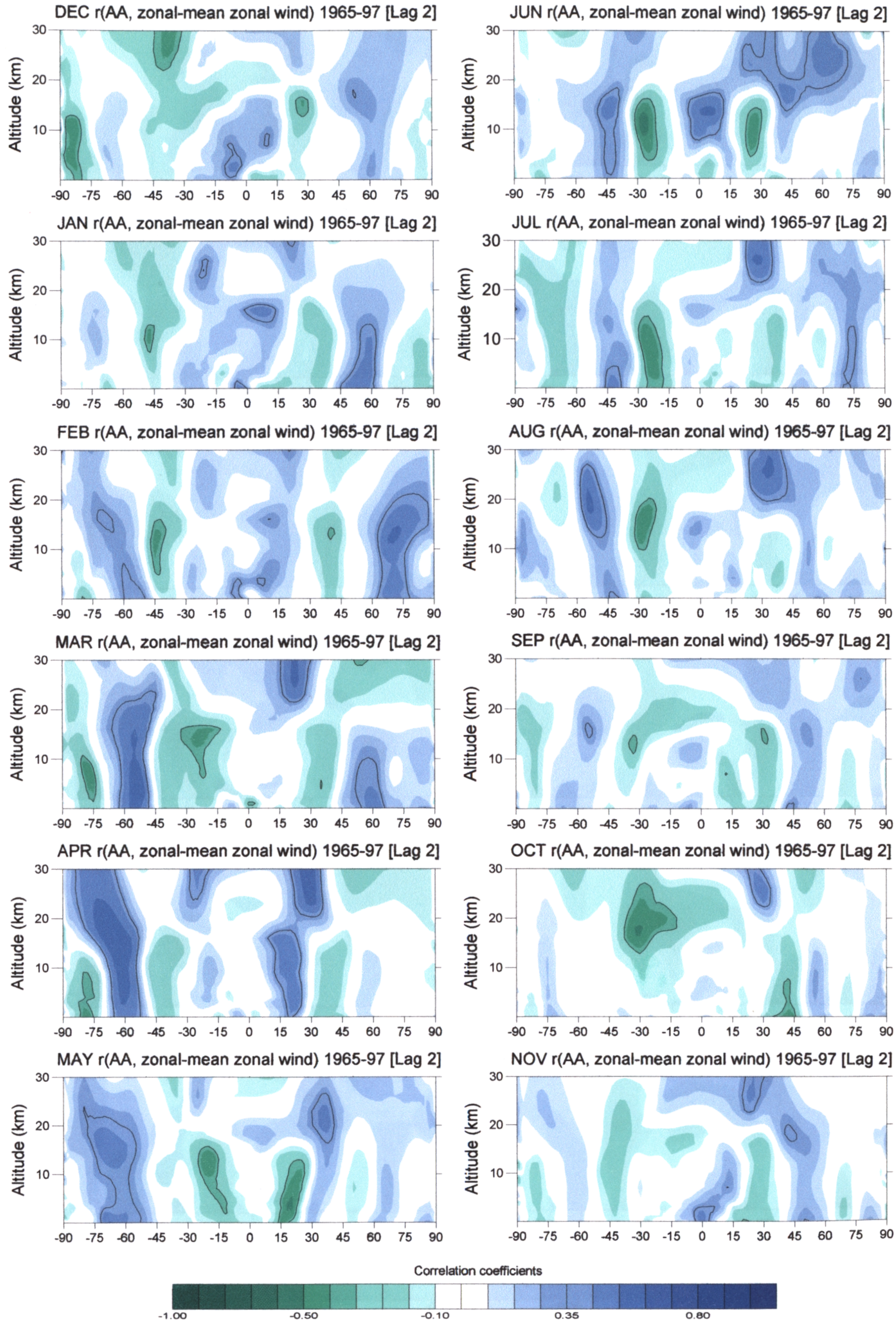

Figure D2. Correlation coefficients between the geomagnetic AA index and zonal-mean zonal wind for each month, lagged by two months. The results do not support the lagged correlations evident in chapter three when the Antarctic and Arctic Oscillation indices are used. There are some strong correlations in the southern hemisphere for March and April, though the spatail pattern of the correlations does not match that of the Antarctic Oscillation.

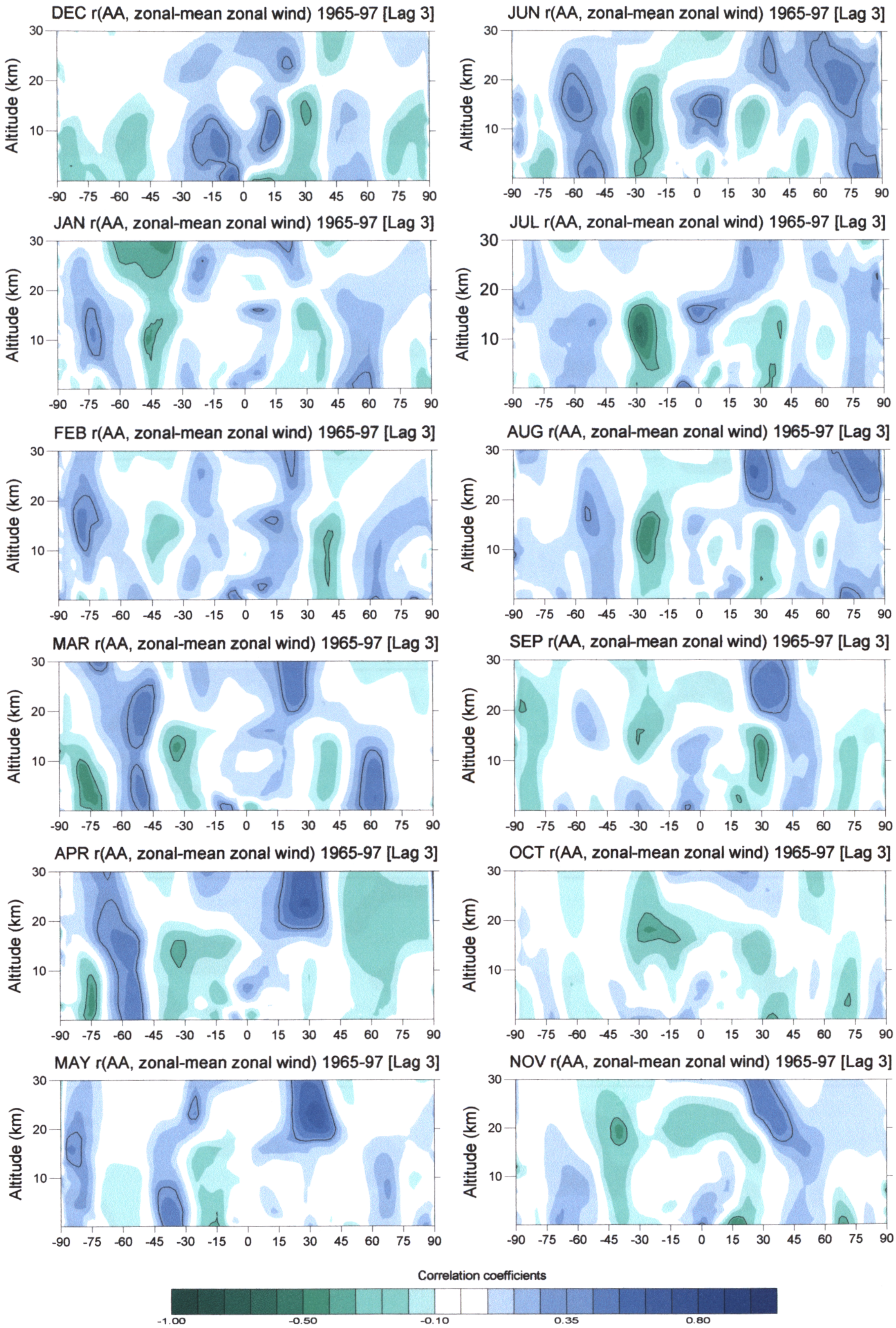

Figure D3. Correlation coefficients between the geomagnetic AA index and zonal-mean zonal wind for each month, lagged by three months. The correlation coefficients are genereally low. The lack of strong correlations at three months lag, especially in January and March, suggests that mechanisms involving the propagation of zonal-mean zonal wind anomalies from the upper atmosphere are unlikely.

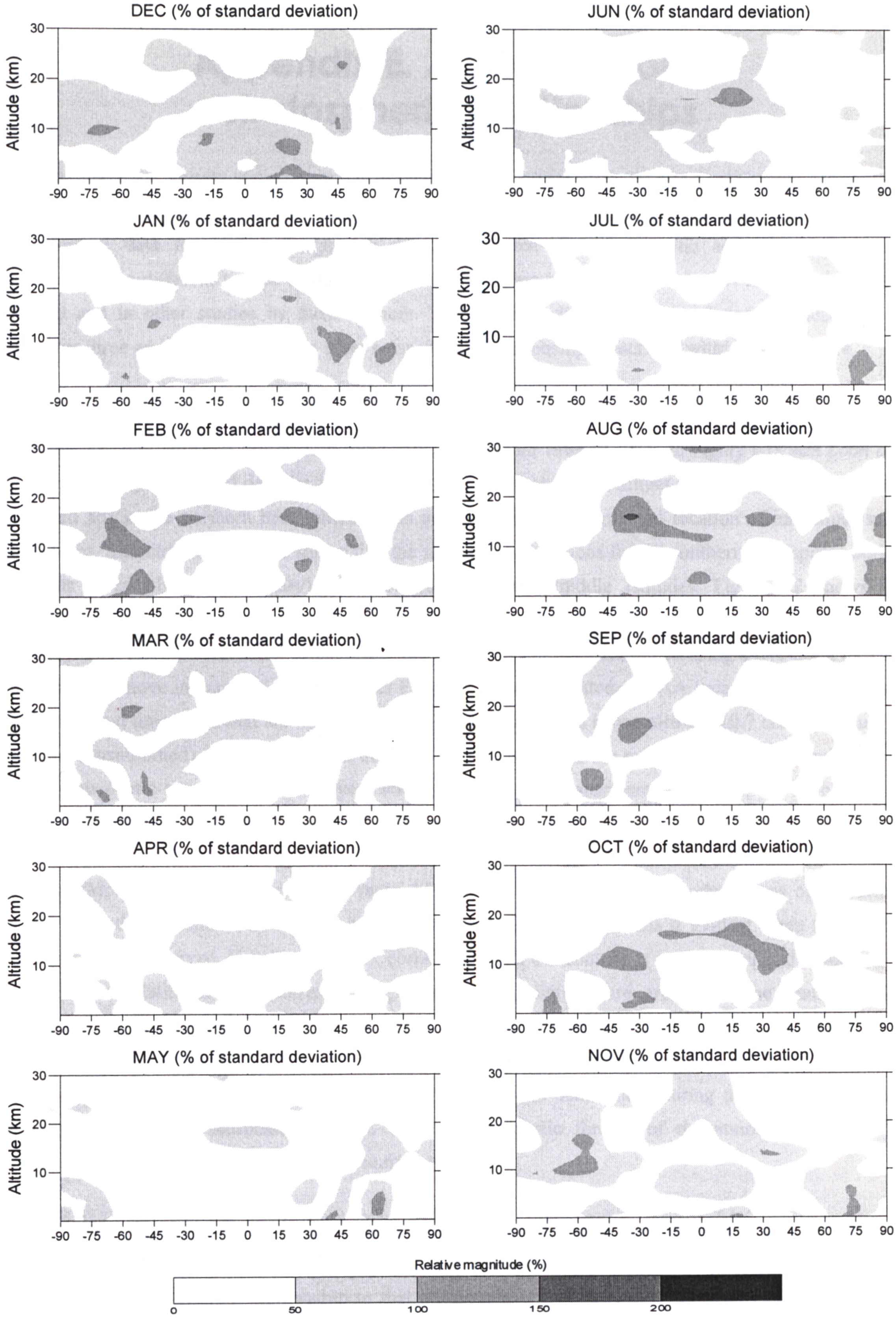

Figure D4. Differences between composites of zonal-mean temperature for high and low geomagnetic activity for each month, relative to the standard deviation. The magnitude of zonal-mean temperature changes associated with geomagnetic activity is relatively small compared to the standard deviation of zonal-mean temperatures.

Appendix E. A comparison of stratospheric relationships

The geomagnetic activity signature in the stratosphere was revealed, in chapter five, through correlations in zonal-mean zonal temperature data. This section uses correlations between the AA index and temperature data for various heights to demonstrate that the geomagnetic activity signal in the stratosphere is different to that of the solar cycle, which has been described in *van Loon and Labitzke (1999)* and in other studies by those authors. The results indicate that the relationship described in chapters three and five is separate to other solar-climate relationships described within the literature.

Figure E1a and E1b, which are from *van Loon and Labitzke (1999)*, show the correlation coefficients between the 10.7 cm solar flux and 30 hPa temperatures from 1968 to 1996. In Figure E1a *van Loon and Labitzke (1999)* have used data for June and July to show that the maximum correlations occur between 10° and 50° in the northern hemisphere – this corresponds to the time and location of maximum solar irradiance. Similarly, Figure E1b shows that the strongest correlations for the southern hemisphere during summer (December and January) occur between low and middle latitudes. Figure E2 shows the corresponding correlations when the AA index is used instead of the 10.7 cm flux for the December-January data. Note that for these calculations, the AA index has been smoothed using a five-point moving average to remove interannual variations. As Figure 2.13 has indicated, the AA index contains variations at interannual timescales that are not evident in the solar cycle (and hence also the 10.7 cm solar flux). If the raw (unsmoothed) AA index is used, the correlation coefficients are overwhelmingly low and indicate that geomagnetic activity does not have a strong signature in temperature changes at the 30 hPa level. Correlations using smoothed data are comparable to those presented in *van Loon and Labitzke (1999)*.

For the December-January average, the main difference is that the maximum correlations occur further south when the smoothed AA index is used rather than the solar flux. This is evident when the $r = 0.5$ contour line is observed. For the AA index correlations, the 0.5-contour is much larger and is located at high southern latitudes. The corresponding solar-flux correlations are greatest in the southern mid-latitudes. The June-July results are not shown because there are practically no correlations that exceed 0.4. This contrasts sharply with the results of *van Loon and Labitzke (1999)*, shown in Figure E1a, which shows a broad area of correlations above 0.4 in the northern hemisphere during these months. It also highlights the strong seasonality evident in the geomagnetic forcing of the atmosphere, which is concentrated in the boreal winter/austral summer months.

These results demonstrate that the comprehensively documented relationship between the solar flux and stratospheric temperature, as described in the series of publications by Labitzke and van Loon (outlined in chapter two), is a different relationship to that of geomagnetic activity and the stratosphere. It must be noted, also, that the correlations presented in this section for the AA index do not play an integral part in the relationship described in chapter three, which is instead focused at lower levels of the stratosphere and has a stronger signature at interannual timescales.

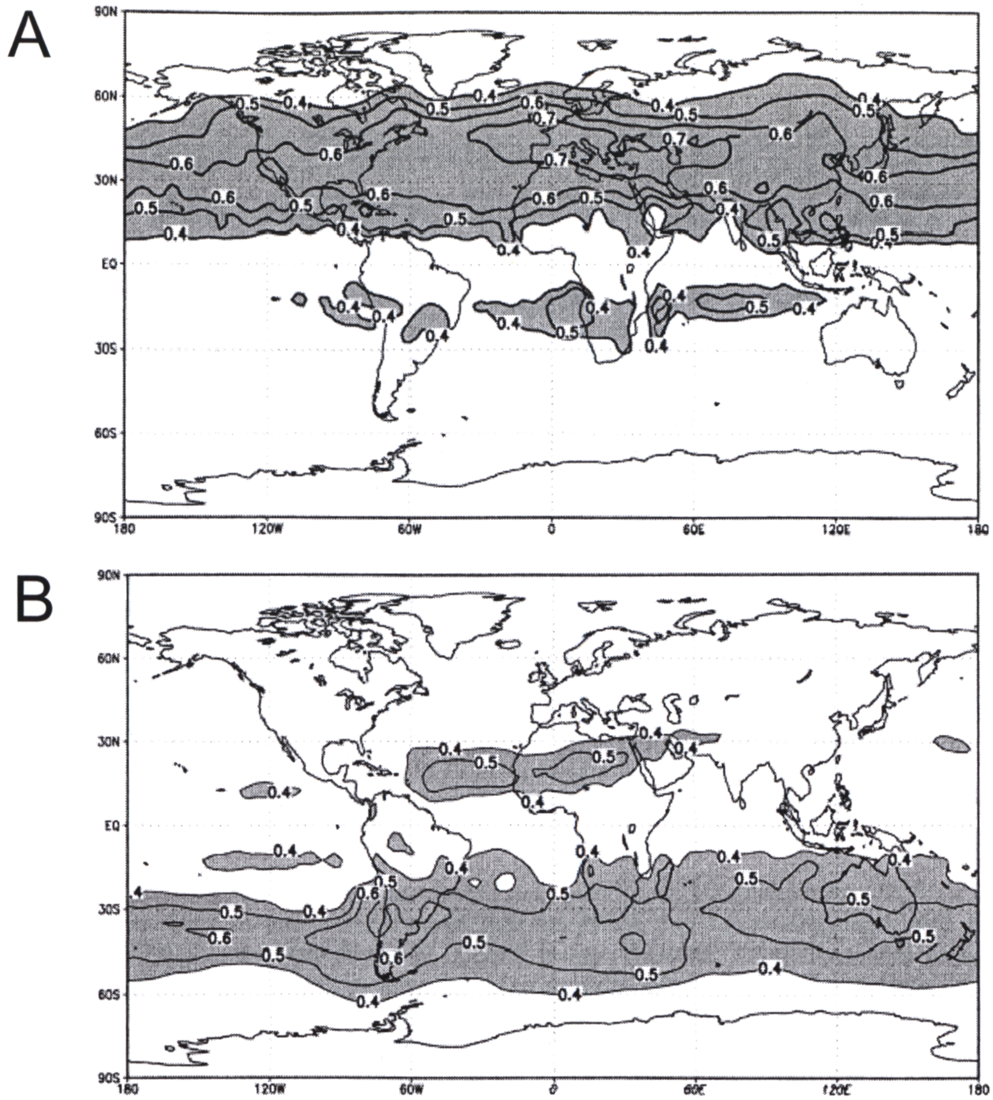

Figure E1. Correlation coefficients between 30 hPa temperature and the 10.7 cm solar flux, 1968-1996 (taken directly from *van Loon and Labitzke*, 1999). (a). June/July, (b). December/January. The spatial pattern of solar cycle correlations to stratosphere temperature described in *van Loon and Labitzke (1999)*, and shown here, differs to the spatial pattern of geomagnetic activity in the stratosphere (Figure E2).

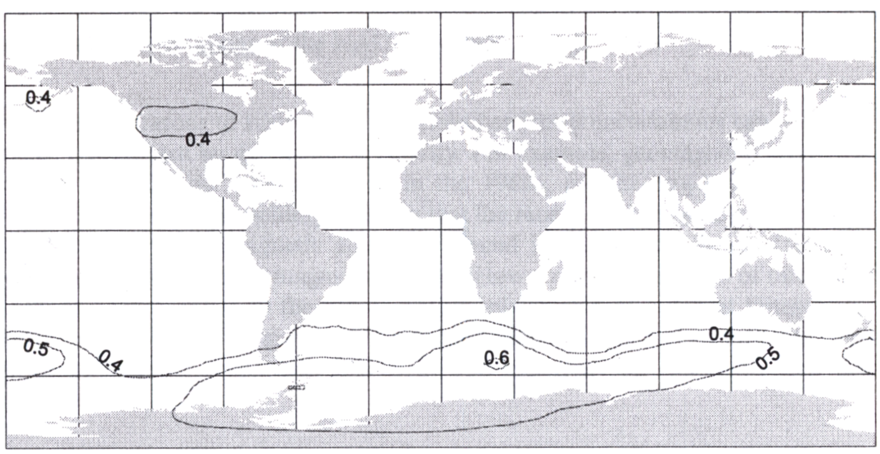

Figure E2. Correlation coefficients between December-January 30 hPa temperature and the smoothed geomagnetic AA index, 1968-1996. Contours below ±0.4 have been suppressed. The AA index has been smoothed using a five-point moving average. The correlations presented here are similar, in magnitude, to the those of *van Loon and Labitzke (1999)*. The spatial pattern of the correlations is different, however. The solar flux correlations are strongest at mid-latitudes and the geomagnetic correlations are strongest towards the pole. This supports the suggestion that the geomagnetic forcing of climate is a separate phenomena to the solar-cycle forcing of the stratosphere.

Appendix F. Palamara and Bryant (submitted to Atmospheric Science Letters, 2002)

Geomagnetic activity forcing of the NAM via the stratosphere

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Abstract

We consider various aspects of the link between solar-modulated geomagnetic activity and the Northern Annular Mode (NAM). Our results indicate that the geomagnetic forcing of atmospheric circulation in the northern hemisphere is temporally and seasonally restricted, modulated by the Quasi-Biennial Oscillation (QBO), and reliant on stratosphere-troposphere coupling. When the data are restricted to January values after 1965, for years in which the January QBO is eastwards, the correlation coefficient between the geomagnetic AA index and the NAM is 0.85. These results can account for many of the enigmatic features of northern hemisphere circulation.

1. Introduction

Changes in atmospheric circulation, as represented by the Northern Annular Mode (NAM), impact upon global climate. Despite the important role that the NAM and the closely associated North Atlantic Oscillation (NAO) index play in recent climate change (Hurrell, 1996; Thompson *et al*., 2000) their forcing mechanisms and behaviour are not well understood (Perry, 2000). For example, it is not clear to what extent changes in the NAO are an accumulation of stochastic weather events (Stephenson *et al*., 2000), the product of ocean-atmosphere coupling (Marshall *et al*., 2001), or the result of internal atmospheric dynamics, possibly originating in the stratosphere (Perlwitz and Graf, 1995). There are also a number of specific uncertainties about these atmospheric modes. Researchers note a period of uncharacteristically low values in the NAO and NAM indices between the 1950s and 1970s (Greatbatch, 2000), followed by a strong positive trend extending to the present day (Stephenson *et al*., 2000). Although Wunsch (1999) has described similar non-stationary periods in a synthetic NAO index, one cannot exclude the possibility that the recent changes in these indices of atmospheric circulation are deterministic. The literature also expresses uncertainty about the origin of decadal variations evident since the 1960s (Hurrell, 1995), the year-to-year winter persistence of anomalies (Stephenson *et al*., 2000), and the nature of interannual variations of the NAO (Feldstein, 2000).

There are a number of reasons to suspect that the aforementioned uncertainties can be explained in part by solar activity, as represented by geomagnetic activity. For example, geomagnetic activity also exhibits an uncharacteristic period of low values centred in the 1960s, and its power spectrum is dominated by decadal variations. The most compelling evidence that the recent changes in these atmospheric indices are related to solar-modulated geomagnetic activity is found in Bucha and Bucha (1998), who presented correlations linking the NAO to geomagnetic activity. However, many aspects of this relationship remain unexplored. These aspects relate to the nature of this relationship at different timescales, especially the interannual level, as well as its temporal and seasonal characteristics, and its possible dependence on the phase of the Quasi-Biennial Oscillation (QBO). In this paper, we test the hypothesis that geomagnetic

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activity is a significant forcing mechanism behind recent changes in northern hemisphere atmospheric circulation changes and examine the aforementioned aspects of the relationship.

2. Data and Methods

Monthly values of the (NAM) are provided online by David Thompson at the Annular Modes website (http://www.atmos.colostate.edu/ao/
Data/ao_index.html). The monthly NAM indices used in our study span 1899 to 2000, and are the same as those used by Thompson and Wallace (2000) and Thompson *et al.* (2000). The geomagnetic AA index was obtained from the NOAA NGDC Solar Terrestrial Physics Division website (ftp://ftp/ngdc.gov/STP/SOLAR_DATA/RELATED_INDICES), and is available from 1868 to 1999. Monthly zonal-mean zonal wind and zonal-mean temperature data were created by averaging the appropriate variables from the NCEP/NCAR Reanalysis data set (Kalnay *et al.*, 1996), available from the NOAA-CIRES Climate Diagnostics Center website (http://www.cdc.noaa.gov/cdc/reanalysis). The zonal wind and temperature data are available for 17 geopotential heights ranging from 1000 hPa to 10 hPa, and 2.5° intervals of latitude and longitude. The data for the QBO, which consist of equatorial 30 hPa zonal wind values, were obtained from the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) website (http://tao.atmos.washington.edu/data_sets/qbo/) and are provided by Barbara Naujokat.

A five point unweighted moving average (i.e. with a half-width of two years) was used to facilitate the study of geomagnetic activity forcing of the NAM at different timescales. Decadal variations were isolated by applying the moving average to the year-to-year variations for each month for both the NAM and AA indices. Short-term (two- to five-year) variations were isolated by subtracting the smoothed data from the original indices. The use of the moving average resulted in the loss of the last two years of data. The decadal and interannual versions of the AA and NAM indices therefore only extend to 1997.

The results of Bucha and Bucha (1998) indicate that the relationship between the geomagnetic AA index and the NAO index, which is tantamount to the NAM index, is not constant over time. Therefore, the temporal nature of the relationship between the AA and NAM indices has been examined objectively for each month using sliding correlations for the decadal (smoothed) data and the cumulative sum of the squares of deviations for the interannual data. For the sliding correlations, 11-year windows were used so that at least one complete decadal cycle was covered, with one-year increments. The cumulative sums technique is demonstrated in Taylor *et al.* (2002), who used it to extract a weak climatic signal from ecological data. It involves calculating the sum of the squares of the differences between two normalised time series. The slope of the cumulative sums reflects the strength of the correlation, uncorrelated data results in a slope of two, while strong positive correlations produce a slope close to zero (Taylor *et al.*, 2002).

One of Pittock's (1978) guidelines to solar-climate researchers emphasises the need to "critically examine the statistical significance of the result, making proper allowance for… autocorrelation and smoothing…". Serial correlation was taken into consideration when performing *t*-tests on correlation coefficients by replacing the actual number of observations with the effective number of observations (N_{eff}), which was calculated as follows (modified from Slonosky *et al.*, 2000):

$$N_{eff} = N \times \frac{(1-|r_1 r_2|)}{(1+|r_1 r_2|)}$$

where N is the total number of observations, and r_1 and r_2 are the lag-one serial correlation coefficients of the two time series under consideration. The original formula in Slonosky *et al.* (2000) does not use the absolute value of the lag-one serial correlations. In this study, it was found that the lag-one serial correlations for the atmospheric indices were sometimes negative, which lead to N_{eff} values that were greater than the original N. The use of the absolute values avoids this anomaly. The use of N_{eff} is especially pertinent to the correlations involving smoothed data, as the smoothing processes greatly increases serial correlation in the data.

3. Results

The magnitude and sign of the sliding correlations (Figure 1) are highly variable with time, indicating that the relationship between geomagnetic activity and the NAM is temporally inconsistent, and that for most months and decades there is no link between the two geophysical parameters. One interval that stands out, however, is the period of positive correlations between the decadal January AA and NAM indices, from 1967 onwards. This indicates that decadal variations in the winter NAM (and NAO), evident since the 1960s, are in-phase with decadal variations in geomagnetic activity. There is also a period of consistently high negative correlations between the decadal August AA and NAM indices from 1930 to 1960. Since our aim is to examine the role of solar-forcing in recent, unexplained, winter circulation changes, we do not discuss the results for the August data further. We note, however, that the correlations for the August data between 1930 and 1960 are strong (r < -0.60) on all timescales, and therefore warrant future attention.

The cumulative sums, calculated for the interannual data, show a similar seasonal and temporal pattern as the sliding correlations. The results for January (Figure 2), in particular, display intervals during which the interannual variations in the AA and NAM indices are correlated. The slope of the cumulative sums is shallow (and hence the correlations are strong) between 1940 and 1950 and from the early 1960s onwards.

For the original (unmodified) January AA and NAM indices, the correlation coefficient between the two series from 1965 to 1997 is 0.62 (N_{eff} = 28), which is statistically significant at the 95% confidence level when N_{eff} is used. Correlations for the interannual variations for the same period (r = 0.49; N_{eff} = 33) are also statistically significant 95% confidence level. The correlation coefficient for the 1965 to 1997 decadal data (r = 0.82) does not yield statistically significant results due to the limited number of effective observations (N_{eff} = 4). This is a result of the smoothing process employed to extract the decadal variations, which has enhanced the already high serial correlation in both the AA and NAM indices. The strong correspondence between the January AA and NAM indices, from the mid 1960s onwards, is shown in Figure 3. Correlation coefficients for other months, even December and February, are considerably lower and do not achieve statistical significance on any timescale.

When describing links between the solar cycle and the lower atmosphere, much of the modern literature indicates that the QBO plays an important role, modulating solar-climate relationships based on the direction of the QBO winds. Labitzke and van Loon (2000), in particular, noted that correlations between stratospheric geopotential heights and temperatures in the Arctic are positive during the QBO west phase, negative during the QBO east phase, and non-existent when the data are not separated according to the QBO phase. It is not clear, however, if geomagnetic forcing of the lower atmosphere is also contingent on the phase of the QBO, especially since the results so far have yielded statistically significant, relatively robust results without any consideration to the QBO.

A strong improvement in the results was evident, however, when the January data were separated according to the phase of the QBO (Figure 4). When the QBO phase is easterly, the January AA and NAM indices are strongly correlated (r = 0.85, N = 15). This correlation is statistically significant at the 95% confidence level, and the improvement in correlation magnitude over the unseparated data is not a function of the reduced sample size. This is evident because the original January AA and NAM indices for QBO west data are poorly correlated (r = 0.38, N = 18) and do not achieve statistical significance at the 95% confidence level. Incorporating the QBO into analysis for other boreal winter months did not appreciably improve the magnitude of the correlation coefficients.

Our analyses so far have revealed that strong correlations between the geomagnetic AA index and the NAM only occur in January, are restricted to periods after the early 1960s (though interannual variations show some correspondence between 1940 and 1950), and are strongest during the QBO east phase. We now examine the spatial signature of geomagnetic activity forcing on zonal-mean zonal wind and temperature data from 1965-1997. Correlations between the unmodified AA index and zonal-mean zonal wind data from the NCEP/NCAR Reanalyses are shown, for December and January, in Figures 5a and 5b. In all cases, $N = 33$, requiring an approximate correlation coefficient of 0.35 for statistical significance at the 95% confidence level. The effective number of observations is not considered because the data have not been smoothed. These correlations include data for both phases of the QBO, and therefore incorporate all years from 1965 to 1997 in order to capture both the decadal and the interannual similarities between the AA and the NAM. When restricted to interannual data for the QBO east phase only, the signature of geomagnetic activity is generally the same but the January correlation coefficients are greater. The geomagnetic activity signature in the January zonal-mean zonal wind data matches that of the NAM. It is characterised by a broad area of positive correlations between 45° N and 65° N, and an area of negative correlations between 15° N and 40° N. Although these correlations extend beyond the troposphere into the lower stratosphere, statistically significant coefficients are limited to altitudes below ~20 km. The dipole pattern of correlations in December, however, is strongest in the stratosphere and is statistically significant only above altitudes of ~12 km. *Christiansen (2002)* indicated that zonal-mean zonal wind anomalies at a geopotential height of 10 hPa and a latitude of 60°N influence the phase of the Arctic Oscillation 30 days later. The correlations shown in Figure 5a for December encompass this area, and suggest that zonal-mean zonal wind variations resulting from geomagnetic activity can influence the January zonal wind field. The correlation between the geomagnetic AA index and the zonal-mean zonal wind at this particular point (60°N, 10 hPa) is 0.44. Correlations for other months (not shown) do not show a pattern similar to the NAM signature in zonal-mean zonal wind, and generally lack statistically significant correlations.

The zonal-mean zonal wind changes associated with geomagnetic activity are accompanied by the zonal-mean temperature changes shown in Figures 5c and 5d. In December, zonal-mean temperatures in the stratospheric polar night region (north of 60°N and above 10 km) are negatively correlated to the AA index. Many of the correlation coefficients in this area are statistically significant at the 95% confidence level. These correlations are matched by positive correlations south of 60°N, still above an altitude of 10 km. In January, the largest correlation coefficients, and subsequently the only ones that are statistically significant, are found lower in the northern atmosphere, below 10 km. This coincides with the spatial pattern of the maximum zonal-mean zonal wind correlations, and may reflect the downward propagation of geomagnetic activity induced anomalies from the stratosphere to the troposphere.

4. Discussion

There is a marked change in the NAM at the beginning of the 1960s associated with the onset of external forcing (Feldstein, 2002). By comparing the trend and variance of the winter NAM for the 1899-1967 period to that of the 1967-1997 period, Feldstein (2002) concludes that the interannual variability for the earlier period is derived from climate noise (i.e. internal forcing), and the latter period is characterised by external forcing. Feldstein (2002) associates the external forcing with either hydrosphere/cryosphere coupling to the atmosphere or a source external to the climate system, such as changes in stratospheric aerosol or ozone concentration. We conclude that solar-modulated geomagnetic activity represents the external process that has forced part of the recent changes in the NAM and NAO.

We therefore attribute some of the winter trend in the NAM index to solar processes associated with geomagnetic activity, which also display an increasing trend since the mid 1960s. Similarly, the period of uncharacteristic low NAM values can be attributed to a concurrent low period in the AA index. The origin of the interannual variations in the NAM and NAO can also be explained in part by this relationship, at least for winters in which the QBO winds are easterly. Our findings also reveal the origin of the decadal variations evident in North Atlantic climate parameters since the 1960s. Tourre et al. (1999) described a quasi-decadal frequency in sea surface temperature and sea level pressure variability in the Atlantic Ocean with a frequency of around 11.4 years. They presented a figure showing that, in recent years, variations at this frequency only occur after 1960 (see their Figure 1b), and indicated that it represents an extension of the North Atlantic Oscillation. Similarly, Venegas and Mysak (2000) note a change in sea ice concentrations and sea level pressures in the North Atlantic between 1950 and 1960.

Decadal variations in both of these climatic parameters are evident from 1960 onwards, but are predominantly a winter phenomenon. Through the analysis of northern hemisphere 500 hPa geopotential heights, Knox et al. (1988) describe a climatic jump around 1962 that marks the abrupt beginning of a different climate regime. The strong correlations between the January AA and NAM indices from 1965 onwards suggest that the onset of solar forcing of the northern hemisphere circulation may be the cause of this regime change and the source of the decadal variations in North Atlantic climate.

Our findings represent a solar-climate relationship that has practical, as well as statistical, significance, evidenced by the importance of the NAM to northern hemisphere climate. The crucial question now relates to how solar/geomagnetic activity is coupled to the lower atmosphere. Part of the mechanism is clear. Geomagnetic activity influences the zonal wind and temperature structure of the stratosphere, which in turn impacts upon tropospheric circulation through a number of possible processes outlined in Shindell *et al.* (2001) and Baldwin and Dunkerton (2001). The seasonality of the relationship is a function of stratosphere-troposphere coupling, which only occurs during winter months.

Further research must consider how these stratospheric changes originate. Crucial to this endeavour is the elucidation of which physical processes in the atmosphere can be associated with geomagnetic activity. It is also important to explain the temporal pattern, as well as the role of the QBO in modulating the relationship. We therefore conclude that geomagnetic activity plays an important role in recent climate change, but that the mechanism behind this relationship needs further clarification.

Acknowledgements

Daniel Palamara would like to thank Alexandra Golab for her revisions of the manuscript and comments regarding the research, and Dr. Adam Burnett for his helpful comments. The authors also thank the individuals and organisations that provided the atmospheric and solar data used in this study.

References

Baldwin, M. P., and Dunkerton, T. J. (2001). Stratospheric harbingers of anomalous weather regimes. *Science* 294, 581-584.

Bucha, V., and Bucha, V. (1998). Geomagnetic forcing of changes in climate and in the atmospheric circulation. *Journal of Atmospheric and Solar-Terrestrial Physics* 60, 145-169.

Christiansen, B. (2002). On the physical nature of the Arctic Oscillation. *Geophysical Research Letters* 29, 10.1029/2002GL015208.

Feldstein, S. B. (2000). The timescale, power spectra, and climate noise properties of teleconnection patterns. *Journal of Climate* 13, 4430-4440.

Feldstein, S.B. (2002). The recent trend and variance increase of the annular mode. *Journal of Climate* 15, 88-94.

Greatbatch, R. J. (2000). The North Atlantic Oscillation. *Stochastic Environmental Research and Risk Assessment* 14, 213-242.

Hurrell, J. W. (1995). Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. *Science* 269, 676-679.

Hurrell, J. W. (1996). Influence of variations in extratropical wintertime teleconnections on northern hemisphere temperature. *Geophysical Research Letters* 23, 665-668.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, Saha, S., White, G., Woollen, J., Zhu, Y., CHelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Repelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R., and Jospeh, D. (1996). The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society* 77, 437-471.

Knox, J. L., Higuchi, K., Shabbar, A., and Sargent, N. E. (1988). Secular variation of northern hemisphere 50 kPa geopotential height. *Journal of Climate* 1, 500-511.

Labitzke, K., and van Loon, H. (2000). The QBO effect on the solar signal in the global stratosphere in the winter of the Northern Hemisphere. *Journal of Atmospheric and Solar-Terrestrial Physics* 62, 621-628.

Marshall, J., Johnson, H., and Goodman, J. (2001). A study of the interaction of the North Atlantic Oscillation with ocean circulation. *Journal of Climate* 14, 1399-1421.
Perry, A. (2000). The North Atlantic Oscillation: an enigmatic see-saw. *Progress in Physical Geography* 24, 289-294.
Pittock, A. B. (1978). A critical look at long-term sun-weather relationships. *Reviews of Geophysics and Space Physics* 16, 400-420.
Shindell, D. T., Schmidt, G. A., Miller, R. L., and Rind, D. (2001). Northern hemispher winter climate response to greenhouse gas, ozone, solar, and volcanic forcing. *Journal of Geophysical Research* 106, 7193-7210.
Slonosky, V. C., Jones, P. D., and Davies, T. D. (2000). Variability of the surface atmospheric circulation over Europe 1774-1995. *International Journal of Climatology* 20, 1875-1897.
Stephenson, D. B., Pavan, V., and Bojariu, R. (2000). Is the North Atlantic Oscillation a random walk? *International Journal of Climatology* 20, 1-18.
Taylor, A. H., Allen, J. I., and Clark, P. A. (2002). Extraction of a weak climatic signal by an ecosystem. *Nature* 416, 629-632.
Thompson, D. W. J., and Wallace, J. M. (2000). Annular modes in the extratropical circulation. Part II: Trends. *Journal of Climate* 13, 1018-1036.
Thompson, D. W., and Wallace, J. M. (2000). Annular modes in the extratropical circulation. Part I: Month-to-month variability. *Journal of Climate* 13, 1000-1016.
Tourre, Y. M., Rajagopalan, B., and Kushnir, Y. (1999). Dominant patterns of climate variability in the Atlantic Ocean during the last 136 years. *Journal of Climate* 12, 2285-2299.
Venegas, S. A., and Mysak, L. A. (2000). Is there a dominant timescale of natural climate variability in the Arctic? *Journal of Climate* 13, 3412-3434.

Captions

Figure 1. Sliding correlations between the decadal variations of the geomagnetic AA and NAM indices. The decadal variations were extracted by applying an unweighted five-point moving average to the original data. The sliding correlation window width is 11-years, with a one-year increment. Correlation coefficients below 0.30 are unshaded. Note the period of consistently high, positive correlations for the January data, from approximately 1967 onwards. This indicates that the geomagnetic forcing of northern hemisphere circulation is temporally and seasonally restricted.

Figure 2. The cumulative sum of squares for differences between the January interannual geomagnetic AA and NAM indices. The stippled line has a slope of two and represents uncorrelated data. The intervals from 1940 to 1950 and from the early 1960s onwards have a small slope, indicating that interannual variations of the geomagnetic AA index are well correlated to the interannual variations of the NAM index for those intervals.

Figure 3. The January geomagnetic AA index (top) and the January NAM index (bottom), from 1965-1999. The correlation coefficient between these two time series is 0.62, which is statistically significant at the 95% confidence level.

Figure 4. Scatter plot of the January geomagnetic AA index and the January NAM index from 1965-1997 for (a) Januaries in which the QBO winds are easterly, and (b) Januaries in which the QBO winds are westerly. The correlation coefficient between these two time series for the QBO east years is 0.85, which is statistically significant at the 95% confidence level.

Figure 5. Correlation coefficients between the geomagnetic AA index and (a) December zonal-mean zonal wind, (b) January zonal-mean zonal wind, (c) December zonal-mean temperature, (d) January zonal-mean temperature, from 1965-1997. The $r = 0.35$ contour is indicated by a solid line, and represents the approximate threshold for statistical significance at the 95% confidence level. Figures 5(a) and 5(b) show that the geomagnetic activity signal is restricted to the stratosphere in December, but is most pronounced in the troposphere during January. The strong similarity between the geomagnetic activity signature in the January zonal-mean zonal wind data and the corresponding NAM signature confirms the reality of the relationship. Figures 5(c) and 5(d) show the corresponding geomagnetic activity signal in temperature data. In December, temperatures in the stratospheric polar region are inversely correlated to the geomagnetic AA index. By modifying the latitudinal temperature gradient of the lower stratosphere, geomagnetic activity is coupled to the troposphere. This is evident in the January correlations, which are strongest in the upper troposphere.

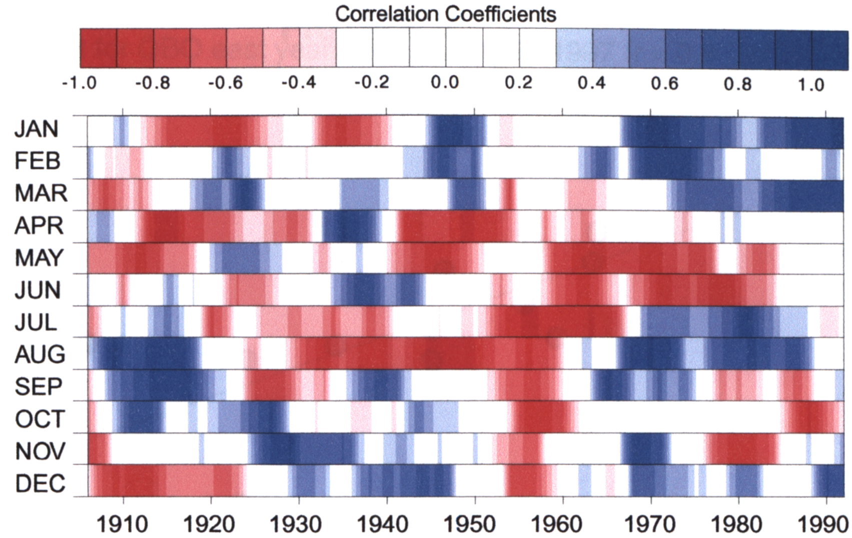


FIGURE 1

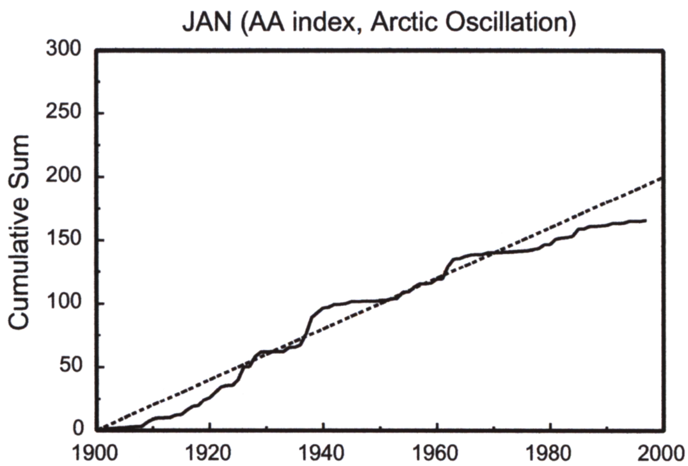


FIGURE 2

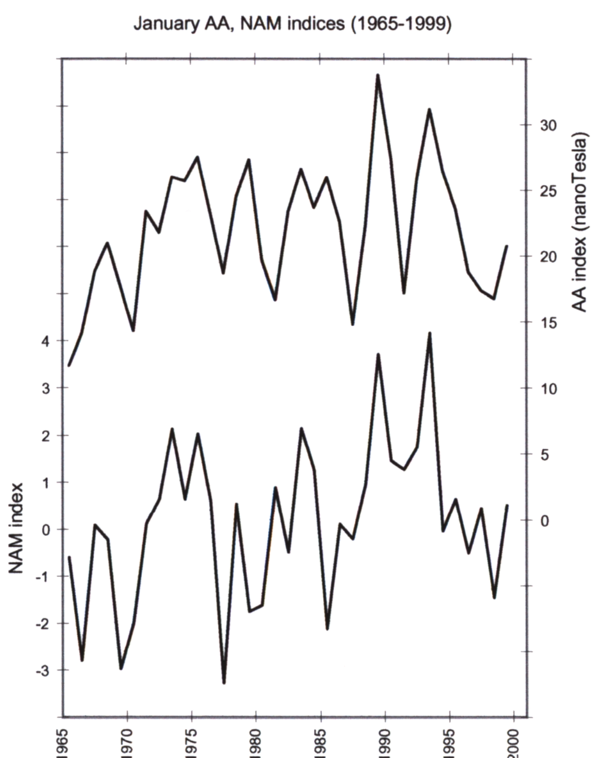
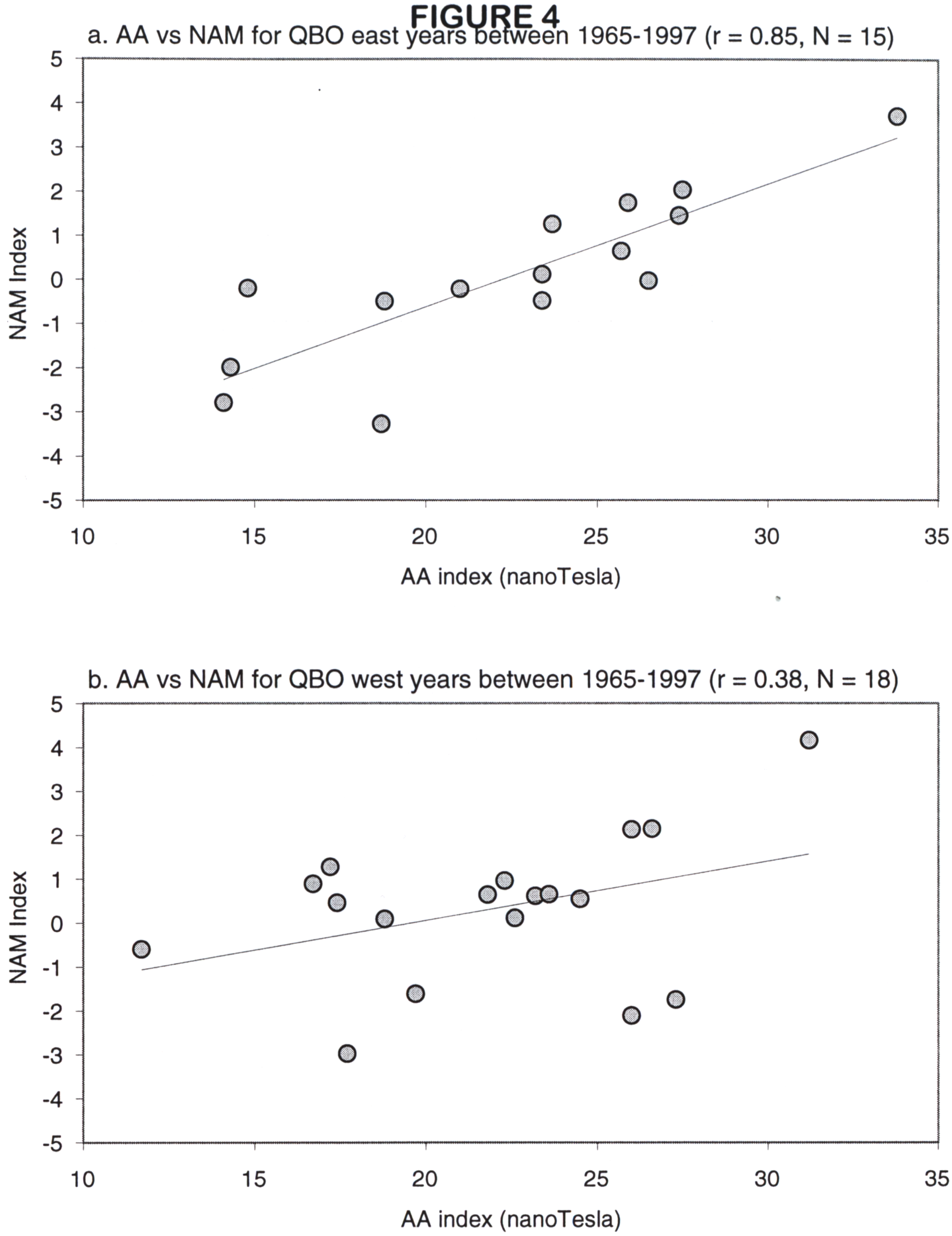


FIGURE 3

FIGURE 4


a. AA vs NAM for QBO east years between 1965-1997 (r = 0.85, N = 15)
NAM Index
5
4
3
2
1
0
-1
-2
-3
-4
-5
10
15
20
25
30
35
AA index (nanoTesla)
b. AA vs NAM for QBO west years between 1965-1997 (r = 0.38, N = 18)
NAM Index
5
4
3
2
1
0
-1
-2
-3
-4
-5
10
15
20
25
30
35
AA index (nanoTesla)

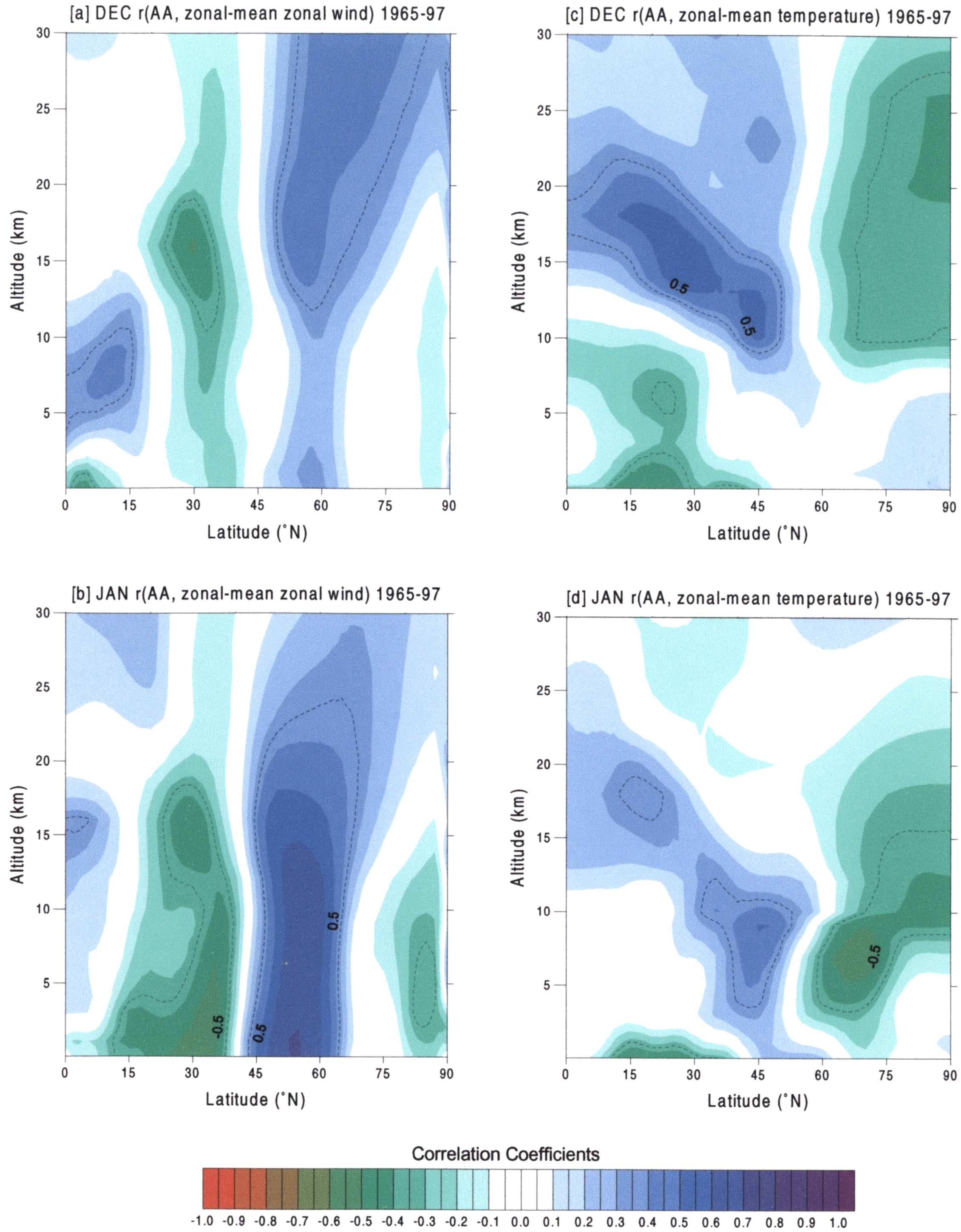

[a] DEC r(AA, zonal-mean zonal wind) 1965-97
[c] DEC r(AA, zonal-mean temperature) 1965-97
[b] JAN r(AA, zonal-mean zonal wind) 1965-97
[d] JAN r(AA, zonal-mean temperature) 1965-97
Altitude (km)
Latitude (°N)
0.5
-0.5
Correlation Coefficients
-1.0 -0.9 -0.8 -0.7 -0.6 -0.5 -0.4 -0.3 -0.2 -0.1 0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

FIGURE 5